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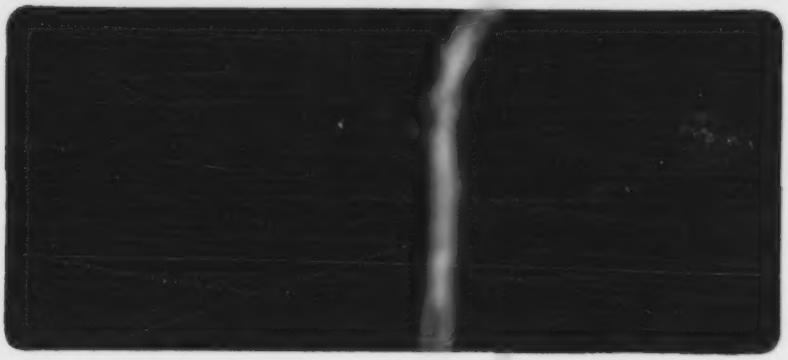

Environment Canada Environnement

Regional program report (Canada. Environmenta
l Protection Service. Pacific Region)
Vol: 90 No: 4 Date: 900500

TD 171.5.C3 R43 2022993I
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ENVIRONMENT CANADA
ENVIRONMENTAL PROTECTION
PACIFIC AND YUKON REGION

# THE GEOCHEMISTRY OF WESTMIN RESOURCES LTD. MYRA CREEK MINE TAILINGS

## After Thirty Months Exposure of Subaerial Tailings

REGIONAL PROGRAM REPORT 90-04

BY

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MAY 1990

91-00670/

**ACKNOWLEDGEMENTS**

The ongoing studies at the Westmin Mines - Myra Falls facility have provided an ideal opportunity to evaluate subaerial tailings deposition, and the effectiveness of this procedure in preventing or mitigating the effects of acid generation from sulphide tailings. The authors gratefully acknowledge the cooperation and participation of Mr. Rudy van Dyk and Westmin Mines.

Mr. Jeremy Haile, P. Eng. of Knight and Piesold Ltd., Consulting Engineers, and Dr. R. Nicholson of the Department of Earth Sciences, University of Waterloo, were most helpful in their technical reviews of the preliminary drafts of this report.

NOTE: This volume contains the main report, the appendices are available in a separate volume available from Environmental Protection, Pacific and Yukon Region, North Vancouver, B.C.

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## EXECUTIVE SUMMARY

Westmin Resources Ltd. operate a 3000 tpd copper-lead-zinc mine 93 km by highway south-southwest of Campbell River in Strathcona Provincial Park. The mine began operations in 1966. Tailings were initially deposited in Buttle Lake; a practice which continued until June 1984 when an on-land tailings disposal facility was commissioned. Mining is primarily from a large sulphide rich orebody and testwork has indicated a significant acid producing potential in the tailings material. Tailings are deposited in the impoundment using the subaerial deposition method; a procedure designed to produce an unsaturated, high density tailings mass with low horizontal and very low vertical permeability.

Environment Canada, Environmental Protection (EP) has conducted a series of studies to evaluate the potential for, and progression of acid generation and contaminant migration in the subaerial tailings mass. Knight and Piesold Ltd. have also conducted studies, primarily to evaluate the structural integrity of the facility. This report describes the detailed study conducted by EP in 1988 after thirty months exposure of the subaerial tailings, summarizes the previous studies of the impoundment, and makes recommendations for future studies.

Initial studies revealed high sulphide contents in the tailings with some segregation of sulphide minerals from acid neutralizing carbonate minerals. Oxidation of the upper 6 cm of the tailings was evident within eighteen months of exposure with low pH and depleted neutralization potentials over much of the surface. There were still however isolated areas of neutral pH on the tailings surface. The degree of oxidation, as indicated by paste pH values was shown to relate to oxygen diffusion coefficients, and in turn to the moisture content of the tailings material.

The 1988 field program included sampling of surface waters, surface solids from both fresh tailings and exposed tailings, and test pit sampling to develop depth profiles in the tailings mass. Solid samples were analyzed for paste characterization. Shake flask extraction tests were also conducted to determine the water soluble fraction of the tailings and the results used to

estimate the extent of acid generation and contaminant migration. Temperature was measured in the solids at surface and over depth in the test pits.

The surface sediment sampling programme and paste analyses indicated that acid generation had progressed in Area #1 in the 12 months since the previous study. The visual appearance of the tailings surface varied from dark grey, wet silty areas to whiter, drier, more sandy areas. Orange/brown zones of surface oxidation were also evident. Surface paste pH values in the exposed tailings were lower than in the 1987 survey, with only small isolated pockets above pH 2.5. Generally, areas of low pH corresponded to oxidizing redox potentials, and high total dissolved solids. Large populations of Thiobacillus ferrooxidans were measured in solids and solution samples from Area #1, indicating that bacterially catalyzed surface oxidation occurred and acid was generated. Relatively fresh tailings, sampled from Area #2, showed statistically significant changes in sulphate, acidity, conductivity, ORP, zinc, and copper values after only six months exposure, except pH and iron values, which did not change over six months.

Test pit sampling to develop depth profiles in the tailings mass included geochemical and geotechnical analyses. Temperature measurements can be useful indicators of the extent of the exothermic acid generating reactions. At this site however the temperature of the tailings solids was also influenced by ambient air temperatures and did not directly indicate sulphide oxidation. The heat capacity of the tailings material varied with both moisture content and mineralogy.

Geotechnical analyses indicated that oxidation occurred in the tailings both from surface extending to depth, and in isolated layers within the tailings, depending on the geotechnical characteristics of the layers and extent of cracking. Shake flask analyses of fresh tailings and samples from layers in each test pit were compared to determine the extent of acid generation and contaminant migration. The locations of "contaminant fronts" were estimated based on arbitrarily determined "elevated levels" of each contaminant. Generally zinc and acidity fronts were most mobile and/or generated most rapidly in the oxidation process and penetrated to the greatest depth in the impoundment. Sulphate ions were probably the dominant ions and contributed significantly to conductivity; these two fronts appeared at

similar depths in many test pits. Copper, iron and pH fronts were generally shallowest, which is reasonable as copper and iron require low pH environments for mobility.

Geotechnical analyses again demonstrated the layered, heterogeneous nature of the tailings with material varying from sand to silt and clay. This layered nature was reflected in the paste pH profiles of several test pits with alternating layers of acidic and near neutral pH values. The degree of saturation of the layers tested varied from 43 % to 94%, and calculated hydraulic conductivity values (Hazen equation) varied from $10^{-3}$ to $10^{-6}$ cm/s.

Migration of contaminants from the surficial oxidized zone was slower than predicted by calculated saturated hydraulic conductivity values. The depth profiles suggested a significant horizontal component of flow (as would be expected from subaerial deposition methods). Since subaerial deposition generally produces an unsaturated tailings mass, the rate of movement of contaminants from the tailings could provide an indication of the potential drainage based on infiltration rates and contaminant concentrations. The presence of a local, and possibly transient, perched water table was suggested by the locations of the contaminant fronts. Further study of contaminant transport and actual pore water sampling to determine in situ contaminant levels would be required.

Detailed sampling in an area of desiccation and surface cracking showed evidence of increased oxidation at depth due to the transport of oxygen and water. The exposed surfaces along the crack showed lower pH and higher acidity, conductivity, sulphate and iron values than the surrounding layer. These cracks appeared to form preferential flowpaths for acidic drainage and also allowed lateral transport of acidic drainage through a more conductive sand layer, thereby contributing to the layered pH and contaminant profiles.

Geochemical and geotechnical parameters were considered together by calculation of oxygen diffusion rates and oxidation rates. The oxygen diffusion coefficient is dependent upon grain size which also determines the residual saturation value of the layer; ie. silt samples with a finer grain size tended to have a higher degree of saturation and a lower diffusion coefficient than sands. Saturated silt layers did appear to hinder oxidation however these layers were prone to cracking due to desiccation. Paste pH and

neutralization potential decreased non-linearly as a function of the diffusion coefficient for surface samples, however a similar correspondence was not found at depth. This could be explained as the overlying strata would control the diffusion of oxygen to the lower strata, and given the layered nature of the tailings, would affect the extent of oxidation at depth.

An approximate rate of oxidation in the tailings impoundment was calculated based on sulphate production and compared with published data (Halbert et. al). The calculated oxidation rates for the Westmin tailings were reasonable in comparison to the published lab data.

The calculated oxidation rates were roughly constant (from 2.8 to $7.9 \times 10^{-2}$ or a factor of about 3) compared to the calculated diffusion coefficients for the surface layers (from 0.0007 to 0.018 or a factor of about 25). Holes with a higher diffusion coefficient and cracking exhibited a greater depth of oxidation. Higher diffusion coefficients also indicated greater oxidation. The effect of cracking on the oxidation rate could not be determined from this sampling program.

The data collected and generated by this laboratory and field study of the Westmin subaerial tailings impoundment describe the baseline conditions in the tailings. The data cannot be used directly to predict the long term behaviour of the tailings facility as it will be covered at closure, however could provide input parameters for modeling of the performance of a cover design.

The reasonably simple techniques used in this study were useful in understanding the factors that have affected acid production and contaminant transport and could be applied to the assessment of other sites. The results are also useful for the design of other subaerial impoundments and to indicate the length of time the tailings could be left exposed without significant acid generation and contaminant migration.

# 1 INTRODUCTION

Westmin Resources Ltd. operate a 3000 tpd copper-lead-zinc mine 93 km by highway south-southwest of Campbell River in Strathcona Provincial Park as shown in Figure 1a. The mine began operations in 1966. Tailings were initially discharged directly to the bottom of Buttle Lake; a practice that continued until June 1984 when an on-land tailings disposal facility was commissioned in the Myra Creek Valley. Tailings are now deposited by the "subaerial" method behind a berm constructed parallel to Myra Creek (Figure 1b). Raw tailings are cycloned to separate the sand fraction which is stockpiled prior to re-use as mine backfill. The finer slime fraction is thickened and deposited subaerially in the tailings disposal facility.

The subaerial method of tailings disposal is designed to produce an unsaturated, high density tailings mass with low horizontal and very low vertical permeability. Tailings are deposited in the impoundment in thin layers on a flat slope from a series of spray bars. Tailings solids settle on the beach as the water drains from the mass and accumulates in a small pond downslope.

Testwork prior to the commissioning of the Westmin tailings disposal system indicated that the tailings would exhibit a potential to generate acid drainage. This potential was expected to increase substantially when the new "HW" mine and mill were commissioned in August 1985. At that time, mining was to begin in a large sulphide rich orebody.

The production of acid drainage from conventional disposal of high sulphide tailings is a recognized phenomenon at mines throughout Canada. At these sites, acid drainage is typically generated in the upper layers of the deposited tailings where air, water, and acidophilic bacteria can interact to oxidize sulphide minerals to sulphuric acid and release associated metals into solution. Acidic solutions generated in the upper zones of the tailings mass infiltrate through the tailings, consuming neutralizing minerals, eventually appearing at the toe of the impoundments as acidic seeps. In some cases the tailings pond supernatant might also become acidified.

The tailings disposal facility at the Westmin site consists of two areas, designated as Areas #1 and #2. Tailings from the Myra-Lynx mine were deposited in Area 1 from July 1984 through to March 1985 when the HW mine was

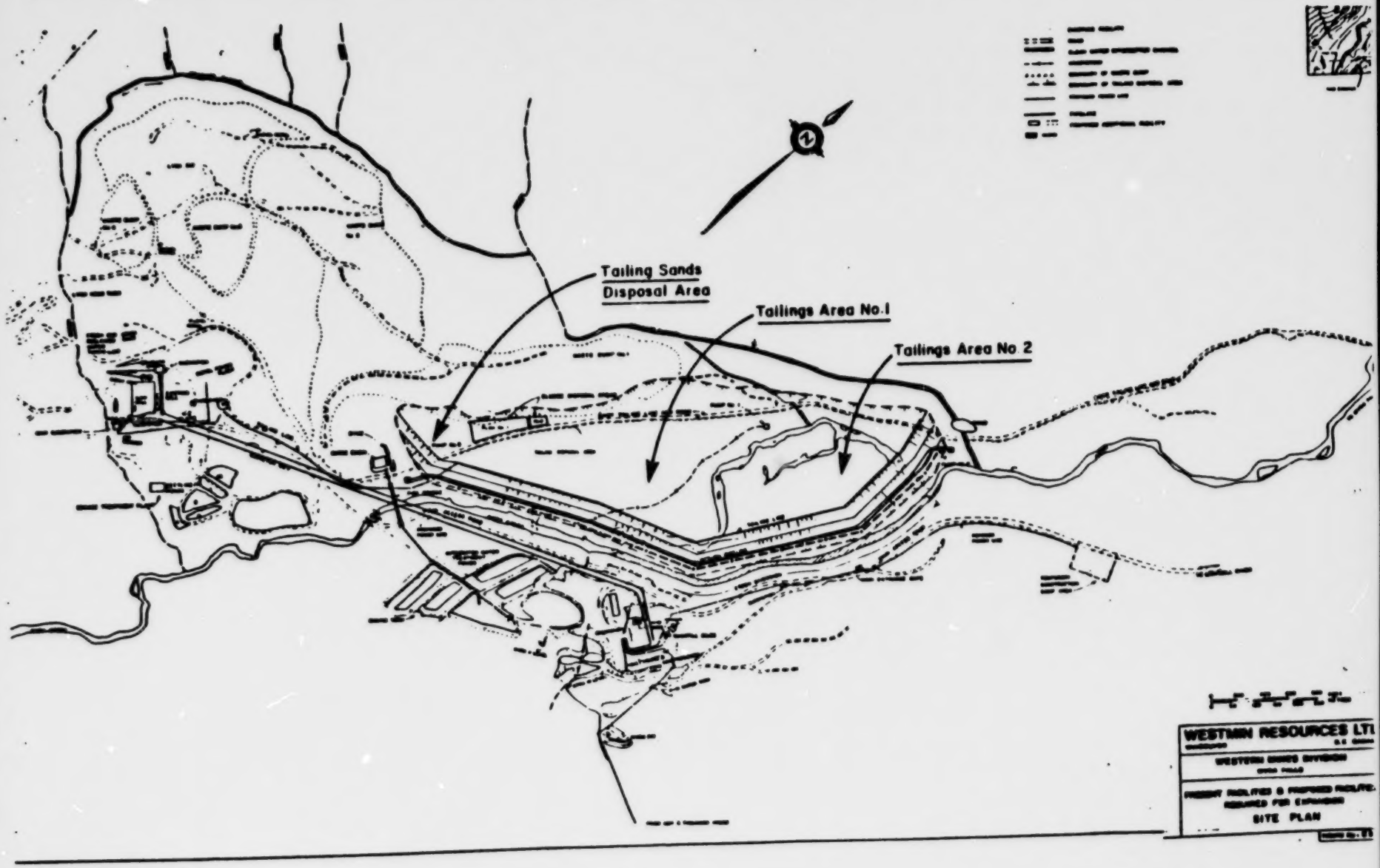



FIGURE 1a WESTMIN RESOURCES - MYRA CREEK MINE SITE PLAN
( Plan Courtesy of Westmin Resources Ltd. )

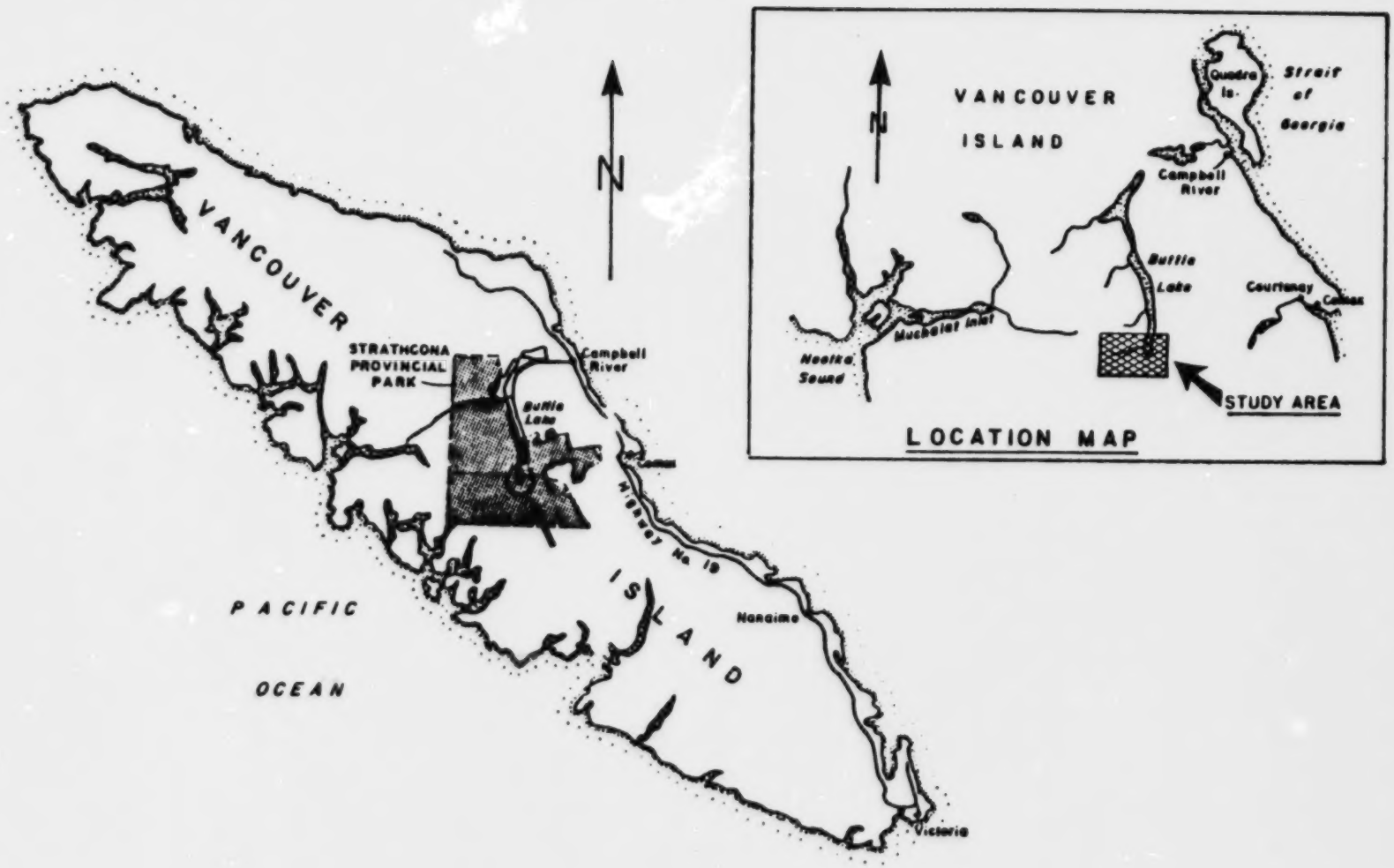



FIGURE 1b LOCATION OF WESTMIN RESOURCES LTD. MINING OPERATION

commissioned. Tailings from the HW mine were deposited in Area #1 through to October 1985, at which time deposition into Area #2 was initiated.

Area #1 primarily consists of tailings deposited by subaerial methods. Some conventional spigotting of bulk tailings was required due to occasional thickener downtime. This was confined to one area at the west side of the impoundment, adjacent to the back drain, from the spigot point at the north side. These tailings consisted of coarser material with a higher sand content than the subaerial tailings. Use of spigotting has been more frequent in Area #2 due to difficulties with thickener operation.

## 1.1 Previous Studies

Studies of the Westmin tailings facility to date, relevant to the potential for acid mine drainage formation, have been conducted by both Environmental Protection (EP) and Knight and Piesold Ltd. The results of these studies are summarized below. Details of each study are available in the referenced reports.

The initial study was conducted by EP in 1985 (Ferguson, 1986) to evaluate the potential for acid generation from the tailings materials after deposition. About 3 m of tailings had been deposited in Area #1, primarily by subaerial methods. The study found that the tailings exhibited significant acid generating potential, with the greatest potential in the material deposited near the spray bars. The data also indicated that some segregation of the dense sulphide minerals was occurring during deposition. Sulphide minerals were concentrated near the spraybars and decreased in concentration towards the backdrain. Acid neutralizing carbonate minerals were more concentrated towards the backdrain. Assays of the metals, particularly iron, in solid samples provided good estimates of the sulphur content. Calcium assays could be used to calculate the neutralization potential.

The second study relevant to the evaluation of potential acid drainage from the tailings facility was conducted by Knight and Piesold Ltd, consulting engineers, in August 1986 (Knight and Piesold, 1986). They conducted a sampling and laboratory testing programme of the Area #1 tailings facility. The focus of the study was to evaluate in-situ geotechnical parameters of the deposited tailings mass to evaluate the structural integrity of the facility.

A total of 15 undisturbed Shelby tube samples were recovered from four test pits; pits A and B near spray bars, Pit C near decant, and pit D near the open ended discharge pipe adjacent to the back drain.

By design, subaerial deposition may limit the production of acid drainage by forming a high density, low permeability mass and thus many of the physical characteristics determined by the Knight and Piesold testwork are relevant to the study of acid drainage potential. These results have been summarized previously (Ferguson, 1987). Briefly:

i) moisture content ranged from 8.1 % to 45.3 %

ii) specific gravity ranged from 3.01 to 3.94, generally lower at depth in test pits A and C corresponding to Lynx tailings, and higher values corresponding to higher sulphide HW tailings

iii) degree of saturation ranged from 27.3 % to 81.8 %

iv) tailings material consisted of partially saturated, non plastic, fine sandy silt with less than 10 % clay, with lenses of moderately to fully saturated, wet silt of low plasticity

v) coefficient of permeability ranged from $5x10^{-8}$ to $7x10^{-10}$ m/s, decreasing with decreasing void ratio.

Chemical analyses were also conducted on representative sub samples of 13 of the 15 Shelby tube samples (Knight and Piesold, Dec. 1986). These analyses confirmed that the tailings material was potentially acid generating (by net neutralization potential calculations) with higher sulphur values associated with the HW material near surface compared to the deeper Myra-Lynx material. Paste pH analyses indicated that acid generation was not occurring in the tailings mass except in one surface sample near the decant outlet.

As recommended in earlier reports, a subsequent study was conducted eight months after the Knight and Piesold study, by EP (Ferguson, 1987) to determine if there was any indication of acid generation in Area #1 after eighteen months exposure, (ie. eighteen months after last tailings deposition). Surface and core samples were collected on April 8, 1987 for both geochemical (paste pH, total sulphur, neutralization potential, and metal scan) and geotechnical parameters (particle size, wet density, dry density, and specific gravity). Calculations of water content, void ratio, porosity, degree of saturation, and permeability were then conducted.

Results of metal analyses of tailings samples collected from Area #2 on July 23, 1986 were also reported. These samples consisted of both unthickened subaerial and spigot deposits.

The study again confirmed the Westmin tailings exhibited a very high potential to generate acid mine drainage based on high sulphide and low carbonate concentrations. The low pH and depleted neutralization potentials of several surface tailings samples indicated that oxidation was occurring at the surface of the tailings mass after eighteen months exposure. A low pH front was identified in the upper six cm of the tailings.

Results of the Environmental Protection, and Knight and Piesold studies indicated the tailings were fine grained, with moderate porosity and relatively low permeability. Most areas were only partially saturated, although finer grained material near saturation was found at the surface.

Good correlation was obtained in the comparison of the degree of oxidation (as indicated by paste pH) with the calculated oxygen diffusion coefficient. The oxygen diffusion coefficient in turn was largely related to the moisture content. The relatively high moisture content of some of the tailings inhibited oxygen diffusion and thus hindered oxidation, although a high moisture content is contrary to the concept of subaerial deposition.

## 1.2 Objectives

The primary objective of the study discussed herein was to determine the status of acid generation in tailings Area #1, after thirty months of exposure, (ie. 30 months since the last tailings deposition). The overall objectives of the ongoing studies of the Westmin tailings facility are three-fold:

i) to determine if the subaerial method of tailings deposition results in a tailings mass exhibiting a low potential for acid production, and;

ii) to determine if the subaerial method of tailings deposition limits contaminant transport through the tailings mass and into the surrounding environment.

iii) to determine if the reasonably simple techniques used in these

studies can be successfully applied to the assessment and prediction of the generation of acid drainage in a tailings mass.

## 1.3 Elements of the Study

An extensive sampling programme was conducted in Area #1 with some sampling in Area #2 for reference. The elements of the sampling programme can be described as follows:

i) Surface samples of tailings - extensively sampled in Area #1 and 3 sites in Area #2. Samples and sites were photographed and samples analyzed for paste pH, total dissolved solids (TDS), and redox potential (ORP), with four samples analyzed for Thiobacillus ferrooxidans.

ii) Surface water samples - collected where available and analyzed for water quality and Thiobacillus ferrooxidans.

iii) Depth profiles - logged and photographed 13 test pits in Area #1 with sampling for paste pH, TDS, ORP, shake flask testing (for dissolved metals, pH, sulphate, alkalinity, and acidity), and selected samples analyzed for neutralization potential and geotechnical characterization (particle size, density, water content).

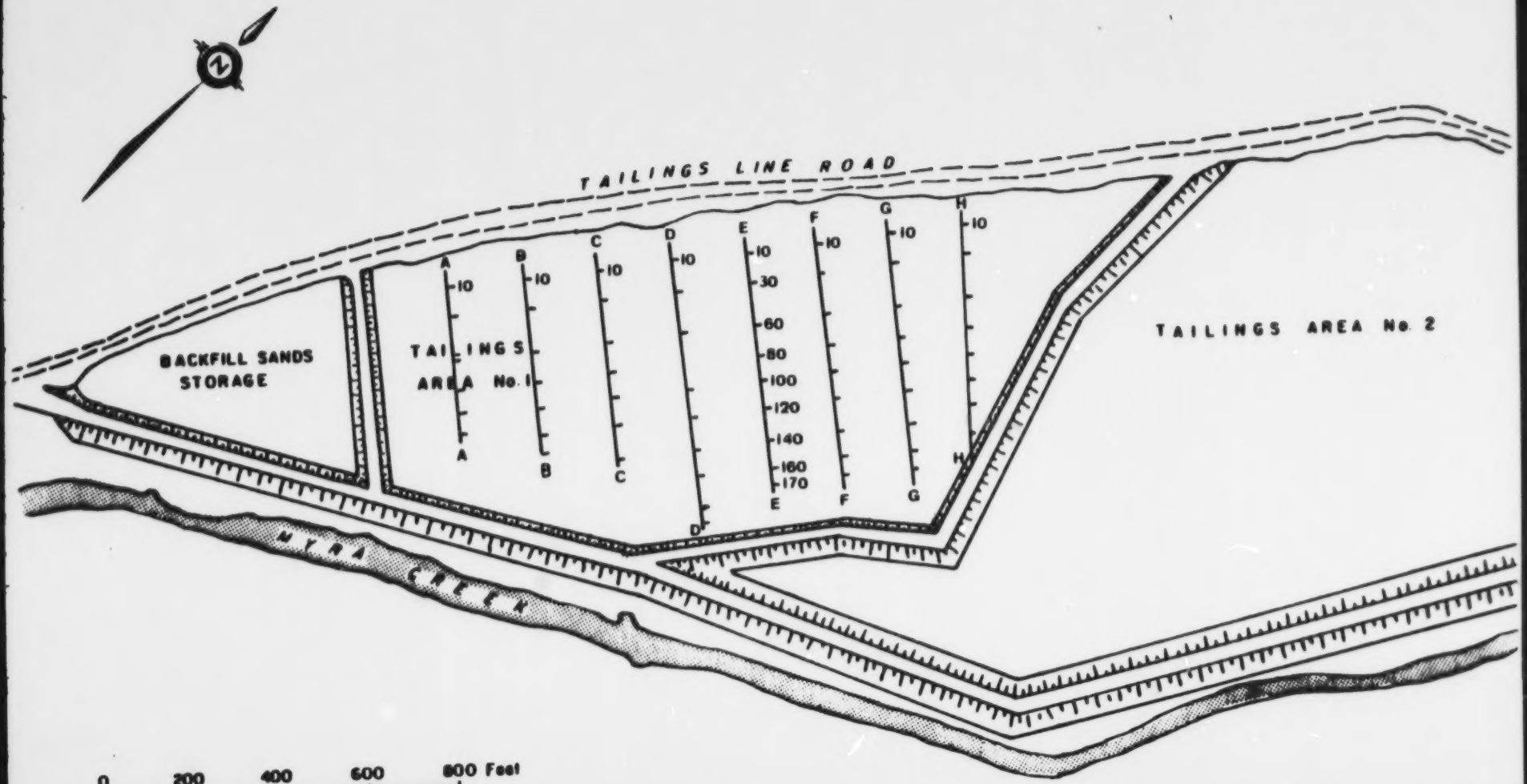

N
TAILINGS LINE ROAD
BACKFILL SANDS STORAGE
TAILINGS AREA No. 1
TAILINGS AREA No. 2
A 10 A
B 10 B
C 10 C
D 10 D
E 10 30 60 80 100 120 140 160 170 E
F 10 F
G 10 G
H 10 H
MYRA CREEK
0 200 400 600 800 Feet
0 50 100 150 200 250 Metres
NOTE. Locations are approximate, distance in metres from drain.

FIGURE 2 WESTMIN TAILINGS SAMPLE LOCATIONS

# 2 SAMPLING METHODS AND ANALYTICAL PROCEDURES

## 2.1 Surface Sediment Samples

The surface sampling pattern of Area #1 is shown in Figure 2. A grid was established consisting of 8 lines approximately 50 m apart extending from the back drain towards the subaerial spray bar beach. A total of 67 samples were collected along these lines, sampling at 10, 30, 60, 80, and 100 m from the back drain, with additional samples from 100 m towards the beach on some lines.

A total of 9 samples were collected from three beaches in Area #2:

i) one beach of fresh tails at the east end, sampled at 100, 110 and 120 m from back drain, (designated SUB 1 to 3 respectively),

ii) beach at east corner of Area #2, tailings approximately 3 months old, sampled at 50, 60, and 70 m from Area #1 berm, (SUB 4 to 6),

iii) beach between Area #1 and Area #2, tailings approximately 6 months old, sampled at 30, 40, and 50 m from Area #2 berm, (SUB 7 to 9).

Three samples were also collected from the tailings sands storage area, consisting of 1 sample of "old sands" from the northwestern corner, and two samples of "newer" sands near the south berm.

Surface samples were collected by recovering approximately the top 2 cm of tailings and placing them in whirl pak bags. Samples were transported to the Environment Canada Laboratories in West and North Vancouver for analyses.

At the EP North Vancouver laboratory, analyses for paste pH, ORP, and TDS were conducted on representative 10 g subsamples mixed with 20 g water, using the respective probes. Determinations of paste pH were conducted according to procedures outlined in Sobek et al. (1978). Four surface sediment samples were also selected for T. ferrooxidans analysis. In this procedure, equal amounts (by weight) of solid sample and buffered water at pH 2 were mixed. Different amounts of the slurry were then added to a nutrient media, and the samples incubated at room temperature for up to two weeks. The samples were then examined for evidence and growth, and the results expressed as "number of Thiobacillus organisms" MPN/100 g.

The 9 samples from Area #2 were analyzed to determine the water soluble fraction of the tailings in shake flask tests using a modification of procedures described by B.C. Research in Report 60601 (Steffen, Robertson and Kirsten, 1987a). A 25 g tailings subsample was oven dried overnight at 110°C and diluted to approximately 80 % volume. The mixture was placed on a shaker table for 12-24 hours and decanted through a GFC filter to remove solids. The solution was sampled for pH, sulphate, alkalinity and acidity analyses. The remaining solution was filtered through a 0.45 micron Sartorius membrane, acidified and submitted for ICP dissolved metal analysis (at the EP West Vancouver lab).

## 2.2 Surface Water Samples

Surface water samples collected from Area #1 consisted of:

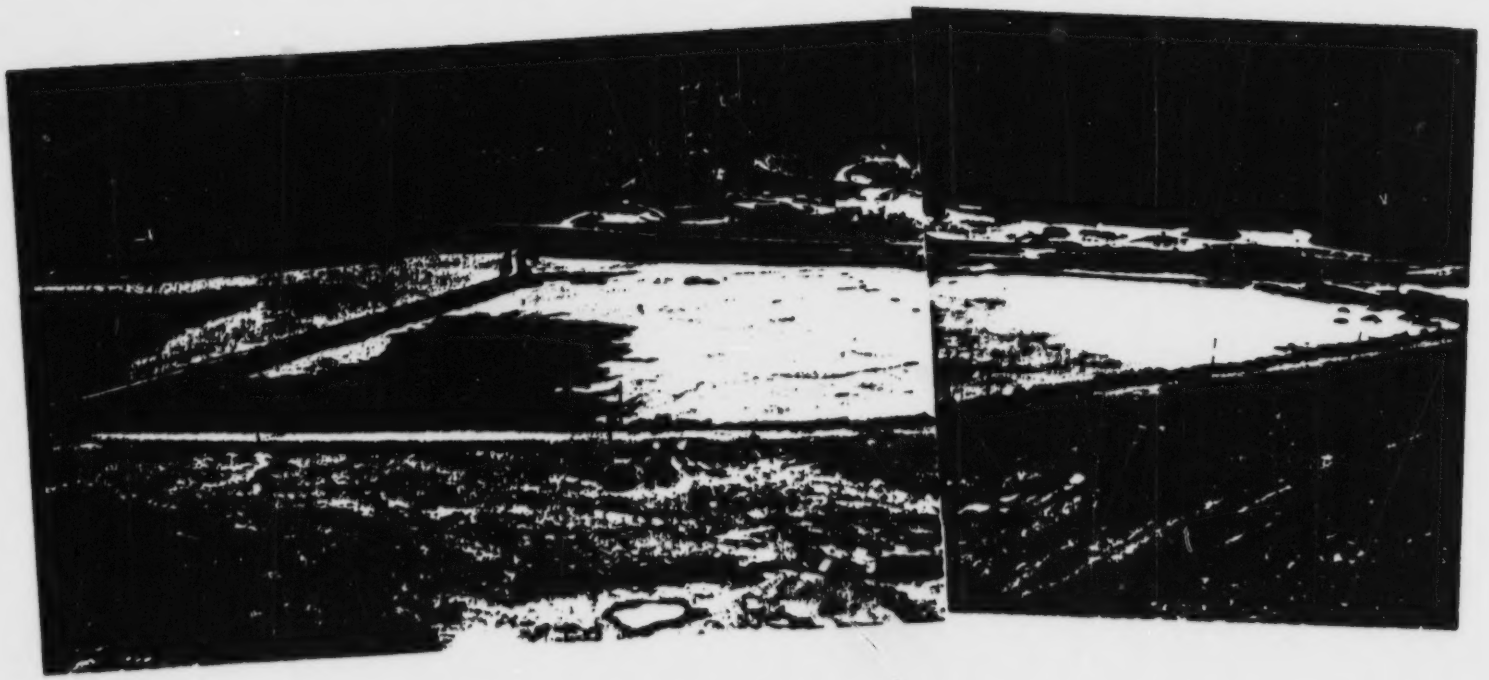
i) 3 samples collected from the eastern end, centre and western end of pool in north east corner (near decant),

ii) 3 samples from water pooled in 3 backhoe test pits in the northwest corner, which were established by the company in 1986/1987,

These samples were analyzed for pH, acidity, conductivity, and dissolved metals by ICP at the Environment Canada lab in West Vancouver. *I. ferrooxidans* analyses and pH determinations were conducted on 3 selected water samples (1 from pool in northeast corner, and 2 of 3 test pit pools). The samples were tested using Most Probable Number (MPN) techniques in the EP Microbiology Lab in North Vancouver.

## 2.3 Depth Profiles

Depth profiles of the tailings were obtained from test pits located as shown in Figure 2 and Photograph 1. A total of 13 test pits were excavated by hand to a depth of about 1 m. Most of the pits were excavated along the E-E line, near the centre of Area #1 extending from the backdrain to subaerial spray bar beach. One auger sample was taken at E160, (ie. along E-E line, 160 m from backdrain), to about 3 m depth. A crack system was identified near



PHOTOGRAPH #1

E140, (ie. along E-E line, 140 m from back drain), and 5 pits were excavated to about 30 cm around the crack system. Four holes were also dug extending from the northwest corner of Area #1 towards the centre in the area of the spigot beach. A second set of holes along E-E were excavated for logging and temperature monitoring at the same distances as described above.

Immediately after excavating each test pit, the layers were logged and sampled by scooping tailings material into whirl pak bags. Discrete layers were visually identified in each pit according to grain size (sand or silt), colour (orange, yellow, etc.), and/or water content (dry, moist, wet).

All samples were transported to the Environment Canada labs for paste pH, ORP, TDS and neutralization potential analyses. Paste pH on all samples and neutralization potential on 39 selected samples (complete for holes E30, E60, E120, E160, E170, A20, and C60) were determined using the procedure outlined in Sobek et al. (1978). Total dissolved solids and redox potentials were measured using the same sample and water content with the appropriate probes. Shake flask tests to determine the water soluble fraction were conducted on all samples using the procedures described above.

The nine surface and eight depth samples collected for geotechnical analyses were recovered using pre-weighed coffee cans. The cans were punctured at the end to allow air to escape and pushed into the tailings. After maximum penetration, the surrounding tailings were excavated and the edge of the tailings at the can edge cut with a taut string. The samples extend to different depths due to the variable sizes of the sampling cans.

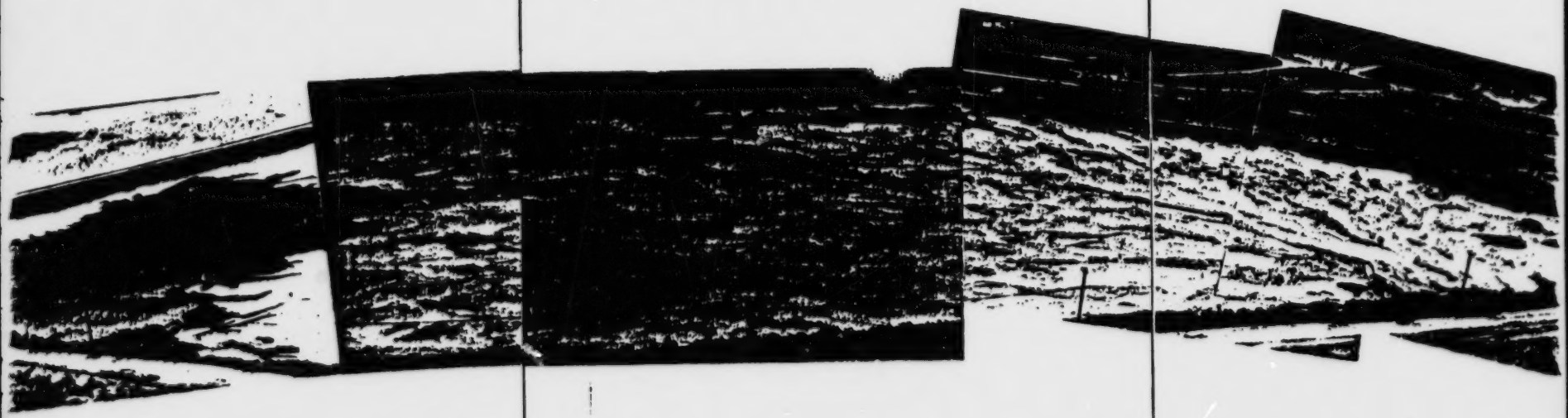
It was intended that the can and tailings would be weighed on-site but this proved impossible due to failure of the field scale. Thus, each sample was carefully bagged and transferred to the EP warehouse and weighed immediately upon receipt. The can contents were then emptied, dried and reweighed. Subsamples were collected and sent to Golder Associates for particle size determinations (both sieving and hydrometer analyses were conducted). It should be noted that despite careful attention to the sample preparation for transport, some leakage and loss of water might have occurred during transport. These geotechnical samples were collected from the surface layers of all 9 pits along the E-E line. Samples were also collected of selected layers at depth in holes E10, E30, E80, E100, E120, E140 (2), and E170 by pushing small cans in the side of the hole at selected layers.

# 3 RESULTS AND DISCUSSION

The results of the testwork are presented in the following discussion. Section 3.1 discusses the surface sediment samples from the "newest" to "oldest" tailings; ie. from the most recently deposited samples of Area #2, through Area #1 and the backfill sands storage area. The surface water sampling programme is discussed in Section 3.2. Section 3.3 presents the results of the test pit sampling programme which was designed to evaluate both the geochemical and geotechnical characteristics of the Area #1 tailings mass over depth. Physical descriptions of the materials observed in the test pits are summarized. The geochemical analyses included in situ temperature measurements, and paste and shake flask analyses of samples taken over depth in each of the test pits. The shake flask extraction tests which were conducted on the newer samples from Area #2, and the tailings which have been deposited for 30 months in Area #1 were compared to evaluate the progression of acid generation. Changes in several parameters which are indicative of acid generation are considered. These data were also used to estimate the position and movement of contaminant fronts within the tailings mass. The term "contaminant" is used to refer to the parameters measured in the shake flask analyses that are commonly used in the evaluation of AMD, eg. pH, acidity, sulphate, dissolved metals. Geotechnical characteristics of the tailings mass are also discussed. Section 3.4 examines the geochemical and geotechnical parameters together to evaluate the degree of oxidation and contaminant transport processes and controls.

## 3.1 Surface Sediment Samples

The general appearance of the tailings mass is shown in Photograph 2. Variations in colour were evident over the surface of the tailings mass and relate to both surface oxidation and variable moisture content. The lighter coloured, whiter areas at the spigot beach to the right were drier and generally sandier material. The dark grey areas corresponded to wetter, siltier tailings closer to the subaerial spray bars near the top of the photograph. Orange/brown zones indicating surface oxidation were evident in



PHOTOGRAPH #2

the pool area at the left of the photograph. Yellow/orange zones were also visible throughout the surface sediments.

Area #2

The results of the paste analyses of samples from Area #2 are summarized in Table 1. These samples ranged in age from fresh tailings to approximately 6 months. All samples were near neutral pH, ranging from 5.9 to 7.1. Total dissolved solids were moderately high, increasing from an average value of 528 to 860 over the 6 month deposition time of the samples.

The results of the shake flask tests to determine the characteristics of the water soluble fraction of the tailings samples are summarized in Table 2. Solution pH values were alkaline and slightly higher than paste pH values, ranging from 7.9 to 8.1, possibly due to exsolution of carbon dioxide and subsequent dissolution of calcium carbonate present in the sample during the shake flask test procedure. The data indicated that acidity, sulphate, conductivity, and zinc concentrations increased with the age of the tailings. Iron values were low (close to the detection limit) and relatively constant at 0.005 mg/l. Copper values were again relatively low with possibly a slight increase in the six month samples (from 0.026 mg/L to 0.052 mg/L).

Statistical analyses (t-test) showed the shake flask and paste analyses (for pH measurements) were significantly different values at the 99 % confidence level. Comparison of the results of each of the shake flask and paste measurements over time (ie. fresh, three month and six month samples) using t-test calculations indicated there were statistically significant changes in some parameters over time:

i) significant increases were shown over six months in acidity (95 %) confidence), zinc (99 %), conductivity (99 %) and sulphate levels (99 %)

ii) pH, ORP, TDS, copper and iron values did not change significantly over six months

iii) significant increases at the 95 % level were evident over three month intervals for acidity, ORP, zinc, and sulphate (0 to 3 months), and copper (3 to 6 months)

iv) significant increases at the 99 % level were evident from three to six months for sulphate and conductivity

## TABLE 1

## SUMMARY OF PASTE ANALYSES

Surface Samples Area #2

| Sample | Age | Paste Analyses pH | TDS | ORP |
|---|---|---|---|---|
| | months | pH units | mg/L | mV |
| SUB 1 | fresh | 6.9 | 515 | -158 |
| SUB 2 | fresh | 6.9 | 630 | -150 |
| SUB 3 | fresh | 6.8 | 440 | -180 |
| mean | | 6.9 | 528 | -163 |
| SUB 4 | 3 | 5.9 | 1053 | -110 |
| SUB 5 | 3 | 6.9 | 480 | -140 |
| SUB 6 | 3 | 7.0 | 765 | -120 |
| mean | | 6.6 | 766 | -123 |
| SUB 7 | 6 | 7.1 | 1185 | -140 |
| SUB 8 | 6 | 6.7 | 572 | -130 |
| SUB 9 | 6 | 6.6 | 823 | -140 |
| mean | | 6.8 | 860 | -137 |

## TABLE 2

## SUMMARY OF SHAKE FLASK RESULTS

Surface Samples Area #2

| Sample* | pH | Acidity | Sulphate | Conductivity | Dissolved Metals Cu | Fe | Zn |
|---|---|---|---|---|---|---|---|
| SUB 1 | 8.0 | 1.4 | 139 | 416 | 0.024 | 0.006 | 0.84 |
| SUB 2 | 8.1 | 1.3 | 150 | 485 | 0.020 | <0.005 | 1.21 |
| SUB 3 | 8.0 | 1.3 | 130 | 390 | 0.035 | 0.008 | 0.41 |
| mean | 8.0 | 1.3 | 140 | 430 | 0.026 | 0.006 | 0.82 |
| SUB 4 | 7.9 | 8.6 | 360 | 880 | 0.023 | <0.005 | 14.0 |
| SUB 5 | 8.0 | 8.2 | 280 | 625 | 0.029 | <0.005 | 15.7 |
| SUB 6 | 8.1 | 3.2 | 196 | 494 | 0.027 | <0.005 | 5.8 |
| mean | 8.0 | 6.7 | 279 | 666 | 0.026 | <0.005 | 11.8 |
| SUB 7 | 8.0 | 8.6 | 710 | 1450 | 0.067 | <0.005 | 13.3 |
| SUB 8 | 7.9 | 20.7 | 840 | 1550 | 0.037 | <0.005 | 20.9 |
| SUB 9 | 8.0 | 16.8 | 710 | 1280 | 0.051 | <0.005 | 19.8 |
| mean | 8.0 | 15.4 | 753 | 1427 | 0.052 | <0.005 | 18.0 |

* units are mg/L except pH - pH units and conductivity - mohs/cm

Area #1

The results of the surface paste pH analyses are summarized in Figure 3a and lines of approximately equal pH have been drawn. Figures 3b and 3c similarly show ORP and TDS values over Area #1. Detailed results are provided in Appendix 1. The surface of the tailings mass was generally acidic with pH values ranging from 2.2 to 4 over most of the area. There were two isolated areas of higher pH; one in the centre of the impoundment, along line E-E with values up to 6.2, and one towards the centre of the berm dividing Areas #1 and #2 with values as high as pH 6.7. The higher pH area near the berm roughly corresponded to the area covered by the pool of water visible in Photograph 2.

Comparison of this Figure with a comparable map from the 1987 study, Figure 4 herein, (Figure 8 in Ferguson, 1987) indicated further oxidation at the surface of the tailings throughout Area #1 over the intervening 12 months as generally pH values on the surface of the tailings have decreased. The surface sampling programme was less extensive in 1987, and the grid less dense, however some comparisons were evident. The higher pH zone in 1988 (Figure 3a) of about pH 5, which was evident in the centre of the impoundment corresponded to an area of high pH (4 to 5.3) identified 1987. Paste pH values surrounding the pocket were less than pH 3.

A marked decrease in pH was evident as the two near neutral pockets noted in 1987 reported values less than pH 3 in 1988 (between lines B-B and C-C at approximately 150 m from the backdrain, and in the northeast corner between G-G and H-H approximately 15 m from backdrain). The area along the east side of the impoundment, surrounding the near neutral pH pocket seen in 1988, (near the berm dividing Areas #1 and 2) was not sampled intensively in 1987. The apparent lack of acid generation could be due to surface ponding inhibiting oxygen diffusion.

Thiobacillus ferrooxidans analyses of the four solids samples from Area #1 all indicated large populations of bacteria, greater than $2.4 \times 10^6$ MPN/100 mL. This again indicates that bacterially catalyzed surface oxidation was occurring and acid was generated.

Surface redox potentials and total dissolved solids values were also mapped and are provided in Figures 3b and 3c. Generally, areas of low pH corresponded to oxidizing (more positive) redox potentials, and high TDS

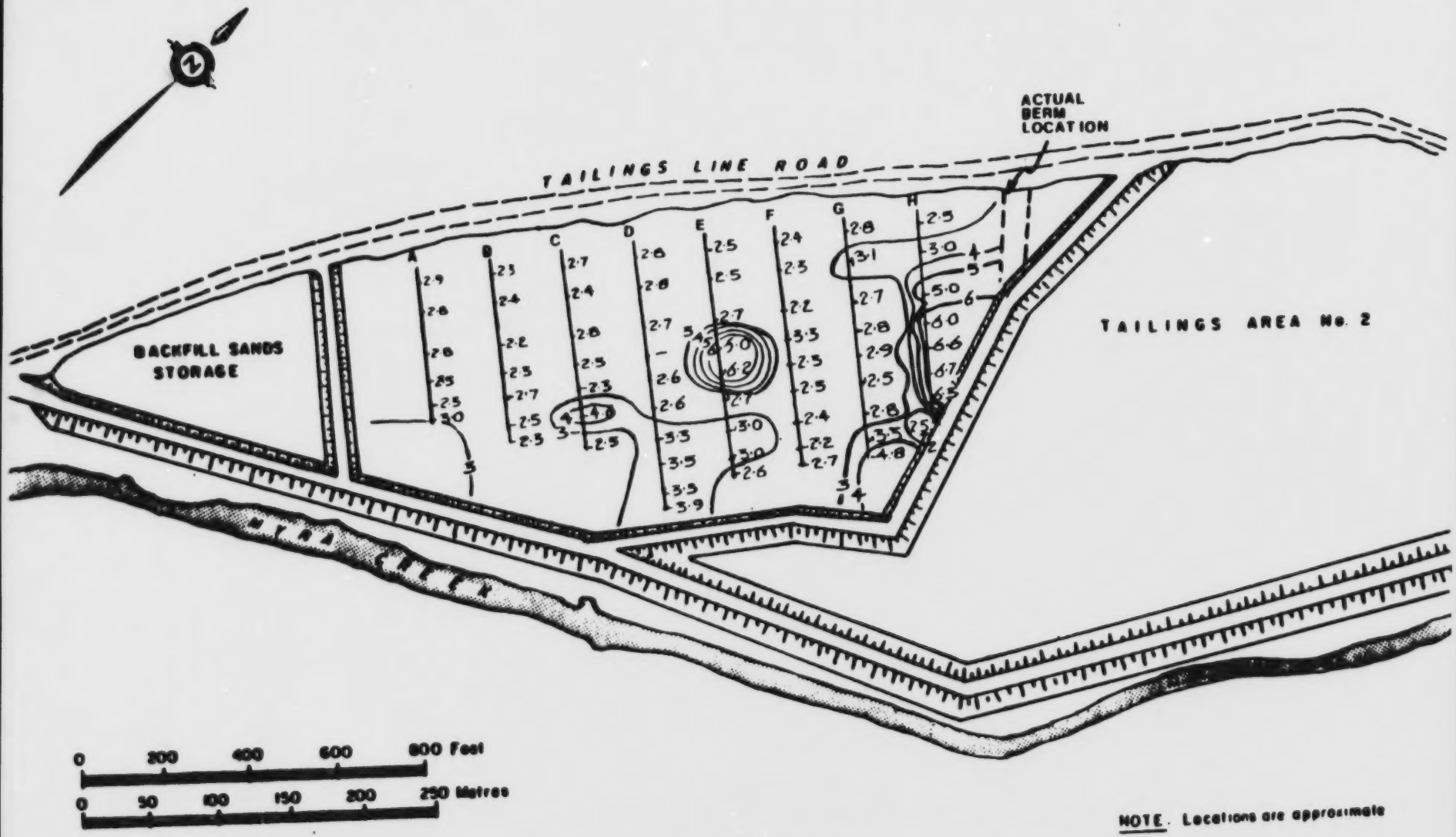



FIGURE 3a SURFACE PASTE pH - MAY 1988

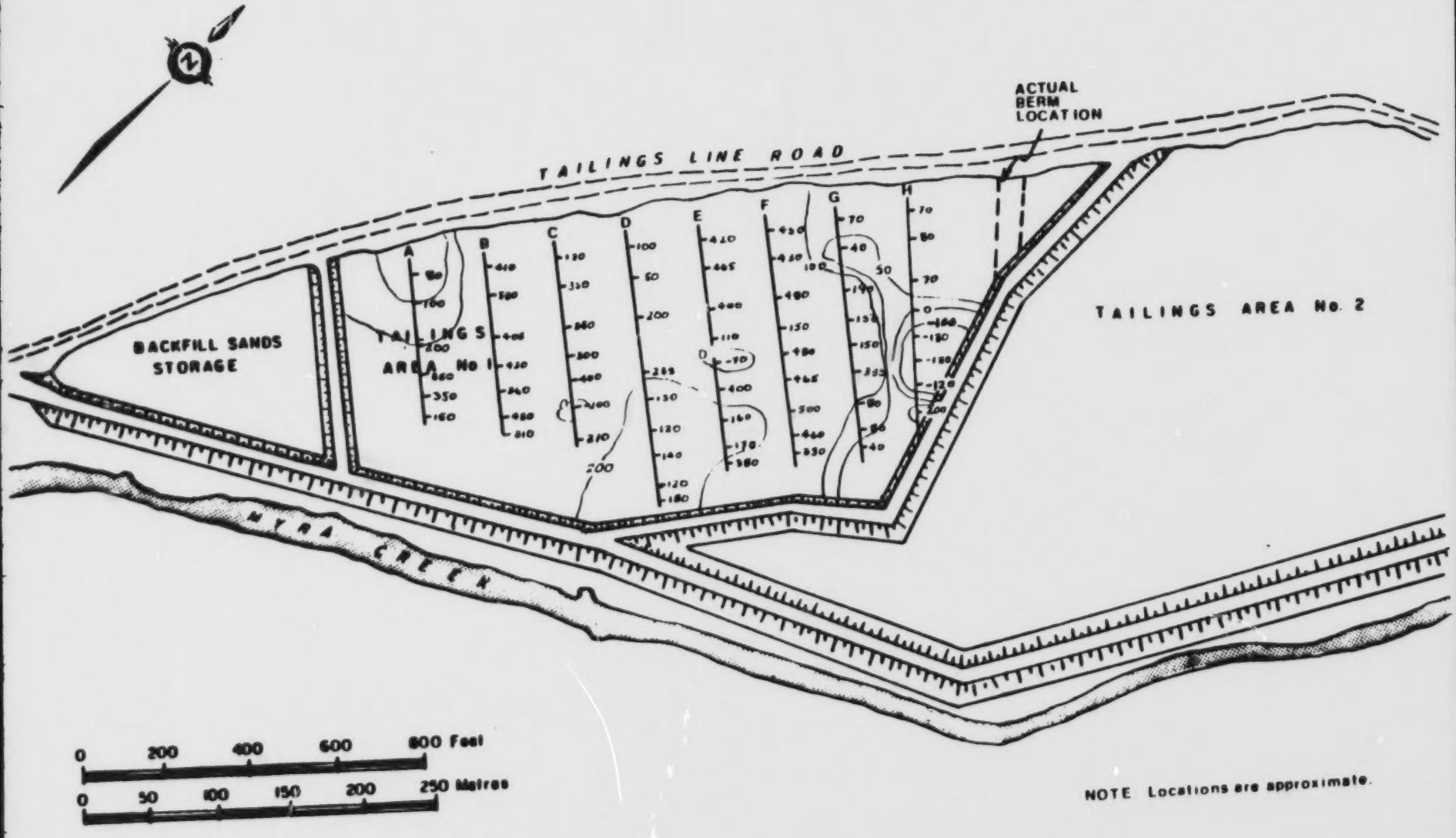



FIGURE 3b SURFACE ORP (mV SCE) - MAY 1988

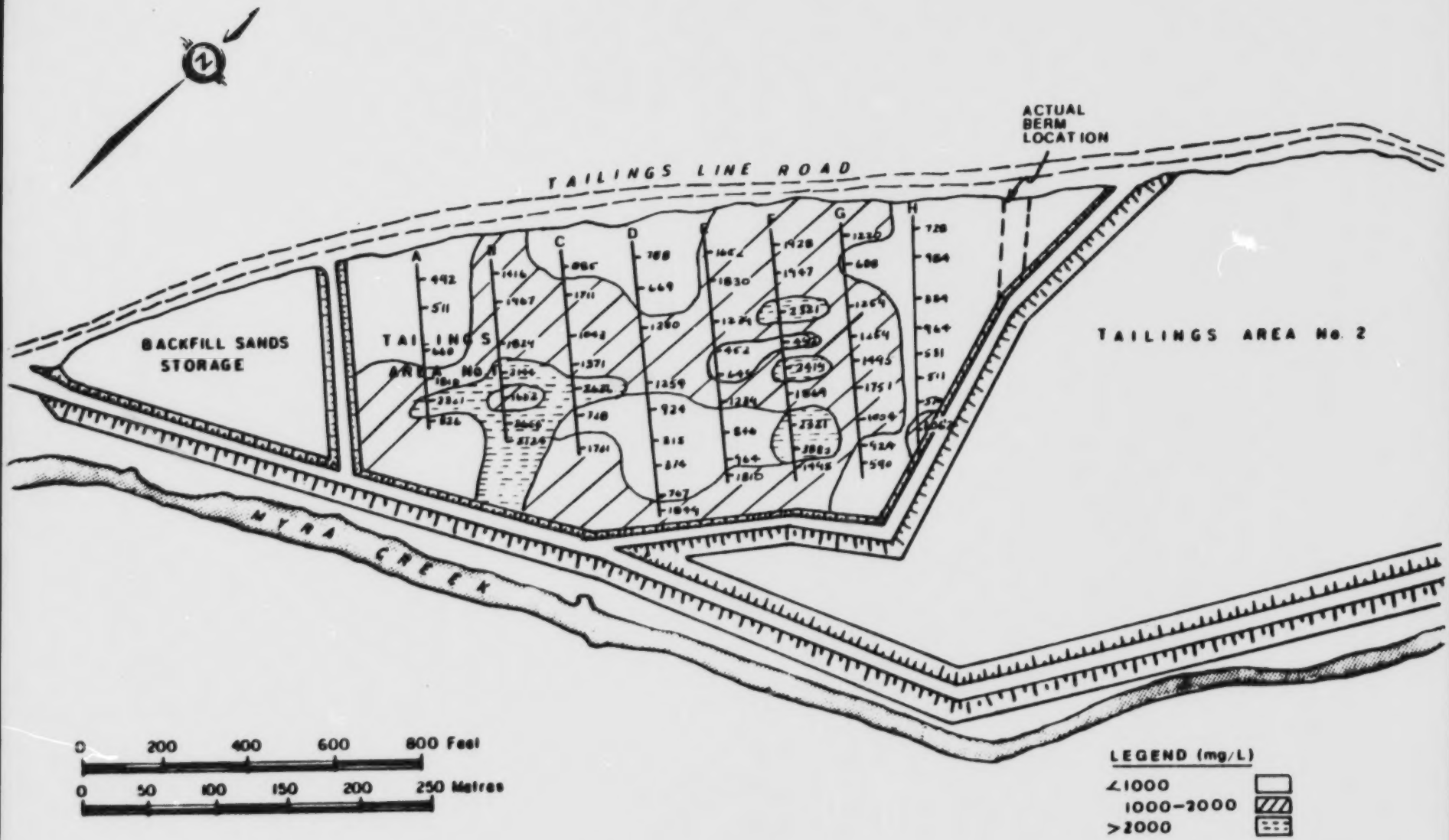



FIGURE 3c SURFACE TDS (mg/L)- MAY 1988

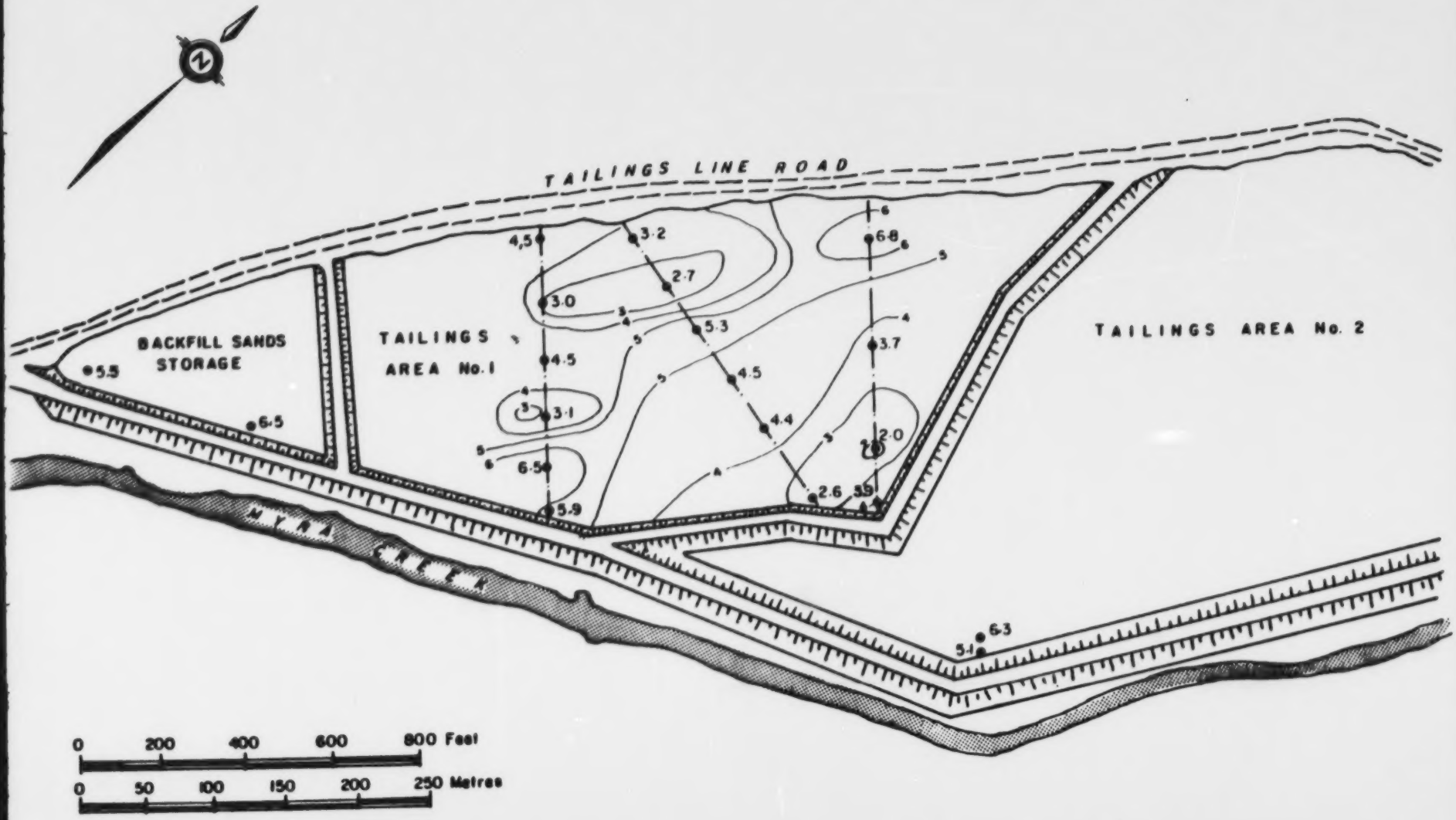



FIGURE 4 SURFACE PASTE pH OF WESTMIN TAILINGS - APRIL 8, 1987

loads. The areas of high pH mentioned above and at station C140 corresponded to negative (reducing) ORP values and relatively low total dissolved loads (less than 1000 mg/L). Stations such as C120, F140, and F160 which showed high TDS values generally corresponded to oxidizing redox potentials (greater than 400 mV SCE) and pH values less than 3.

## Backfill Sands

Samples of the cycloned sand fraction which was stored prior to use in the backfill plant, were analyzed with results as shown in Table 3:

**TABLE 3**

**SANDS STORAGE AREA SAMPLES**

| SAMPLE | pH | TDS mg/L | ORP mV SCE |
|---|---|---|---|
| 1 | 6.0 | 210 | -120 |
| 2 | 6.6 | 285 | -130 |
| 3 | 6.6 | 440 | -120 |

These results did not indicate that acid generation had occurred in the sands, although the sampling was limited and accurate records of the time of deposition of each of the samples were not available. It was suggested by mine personnel that Sample 1, was 3 to 4 years old, and Samples 2 and 3 were relatively recent. It was not clear why these samples did not indicate oxidation, unless they were all relatively fresh samples.

## Summary

The surface sediment sampling programme and paste analyses indicated that acid generation progressed in Area #1 in the 12 months since the previous study. The visual appearance of the tailings surface varied from dark grey, wet silty areas to whiter, drier, more sandy areas. Orange/brown zones of surface oxidation were also evident. Tailings from Area #2 which had been exposed for up to 6 months showed statistically significant changes have

occurred in sulphate, acidity, conductivity, ORP, zinc, and copper (for at least 95 % confidence). Generally, all parameters increased in concentration with time of tailings exposure, with the exception of pH and iron values, which did not change over six months. Surface paste pH values were lower than in the 1987 survey, with only small isolated pockets above pH 2.5. Generally, areas of low pH (less than pH 3) corresponded to oxidizing (greater than 400 mV SCE) redox potentials, and high total dissolved solids (greater than 2000 mg/L). Large populations of Thiobacillus ferrooxidans were measured in the four solids samples from Area #1, indicating that bacterially catalyzed surface oxidation occurred and acid was generated. The samples from the backfill sands area did not indicate oxidation, although the samples were thought to be up to four years old. It was not clear why these samples did not indicate oxidation, unless they were relatively fresh samples.

## 3.2 Surface Water Samples

The results of the surface water chemistry analyses are provided in Table 4. The pond in the northeast corner of the impoundment was acidic (pH 3) with slightly elevated acidity, conductivity and sulphate levels. Dissolved copper, iron and zinc levels were also elevated in the water samples. Results of the water sampling within the backhoe pools are also provided in Table 4. The northwest corner pits were both acidic, with high levels of T.ferrooxidans (>2.4 $x10^5$ and 92,000 MPN/100 mL respectively) whereas the southeast corner pit was neutral with less than 20 MPN/100 mL I. ferrooxidans. The source of the contaminants and bacteria in the surface waters was likely to be acidic runoff from oxidized surface areas of the impoundment.

## TABLE 4

## SUMMARY OF WATER QUALITY RESULTS

Surface Samples

| Location* | pH | Acidity | Sulphate | Conductivity | Dissolved Metals Cu | Fe | Zn |
|---|---|---|---|---|---|---|---|
| Pond NE Corner | | | | | | | |
| - eastern end | 3.0 | 113 | 240 | 780 | 1.12 | 13.4 | 6.73 |
| - centre | 3.0 | 114 | 260 | 780 | 1.08 | 12.8 | 6.58 |
| - western end | 3.0 | 111 | 250 | 780 | 1.03 | 12.7 | 6.58 |
| Pool in Backhoe Pit | | | | | | | |
| - northwest corner | 3.2 | 51.8 | 73 | 390 | 0.16 | 4.69 | 0.31 |
| - northwest corner | 3.0 | 112 | 250 | 780 | 1.04 | 12.6 | 6.63 |
| - southeast corner | 7.7 | 15.1 | 870 | 1480 | 0.01 | 0.06 | 17.7 |

* units are mg/L except pH - pH units and conductivity - mohs/cm

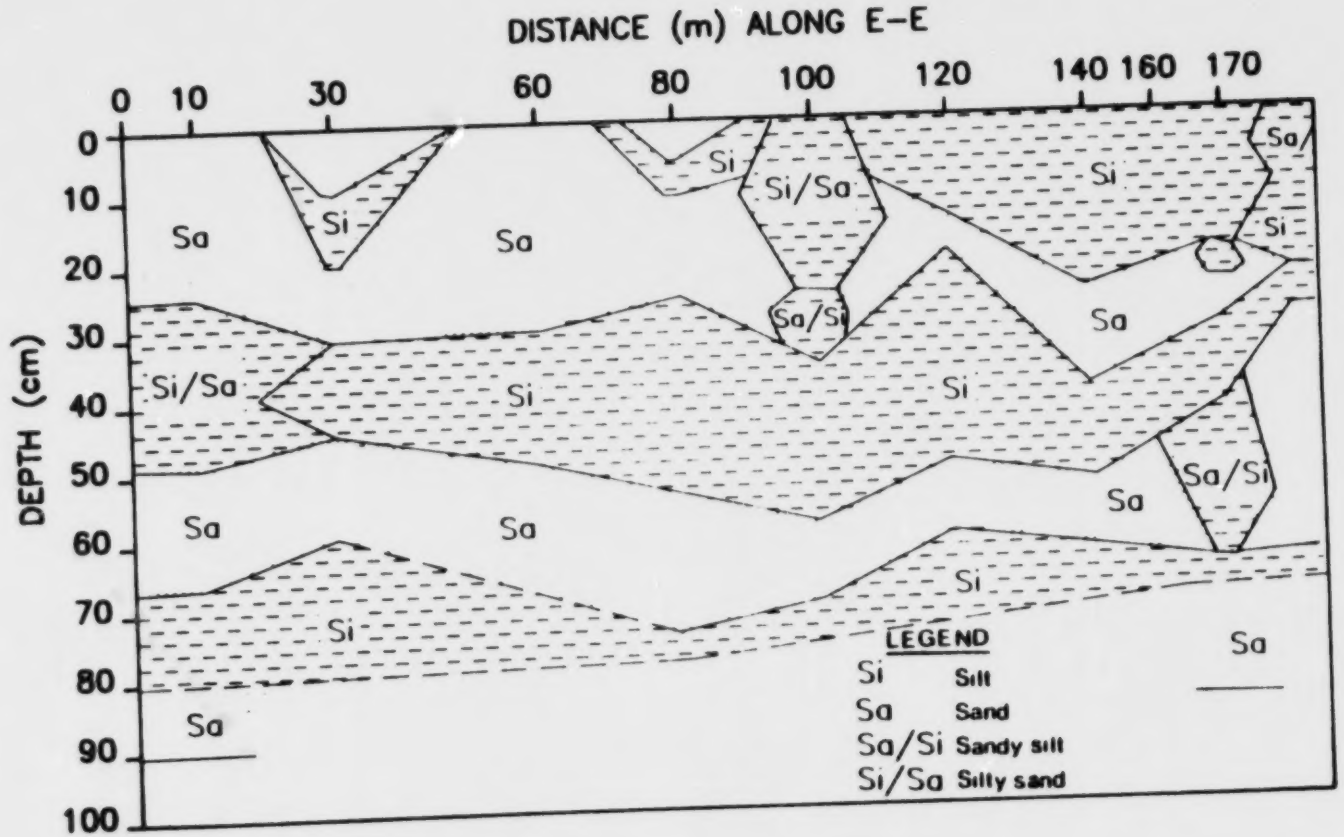



FIGURE 5 DEPTH PROFILE ALONG LINE E-E - AREA 1

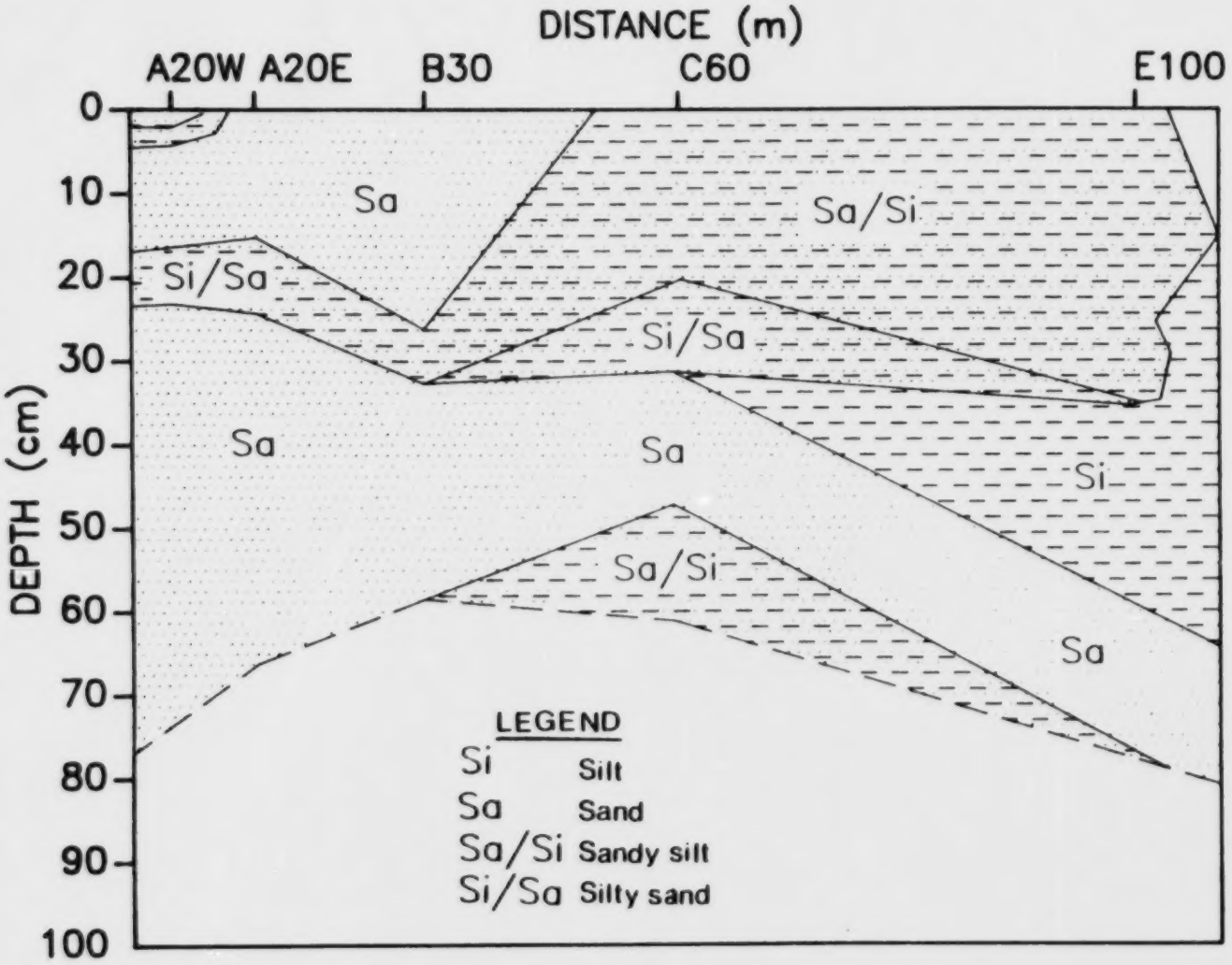



FIGURE 6 DEPTH PROFILE FROM A20 TO E100 - AREA 1

## 3.3 Depth Profiles

The logs of each test pit are provided in Appendix 2. The log descriptions of the test pits along E-E and from A20 to E100 were used to construct the fence diagrams of Figures 5 and 6. These diagrams provide an approximate description of the layering of sands and silts within the tailings mass. These fence diagrams however do not reflect the surface topography of Area #1 as no survey data was available. The log descriptions indicated the variation that was visible over a small interval in a test pit. The sampling intervals within the test pits for the material for particle size determinations used in the fence diagrams were relatively large, and these diagrams are therefore only approximate descriptions.

In the subaerial deposition method, the tailings are sprayed in thin layers over the impoundment area and, theoretically, will settle into layers of sand overlain by finer silts. It is evident from the diagrams that layers of material varying from sands to silts have formed in the tailings mass as designed. The layers however did not appear to be continuous across the impoundment and varied in thickness. In the upper 30 cm of the tailings, zones of sand, silt and silt/sand mixes were noted rather than layering of the tailings. Between approximately 30 and 50 cm, and deeper than 70 cm, silty material predominated, with a sandy layer between, from approximately 50 to 70 cm.

The physical appearance and composition of each of the test pits can be useful in understanding the geochemical and geotechnical data, and detailed descriptions of each of the test pits are provided with the following discussion of the geochemical analyses.

### 3.3.1 Geochemical

#### Temperature Profiles

The sulphide oxidation reactions which generate acid drainage are exothermic in nature and temperature measurements are often a useful parameter in assessing acid generation at a site. Surface sample temperatures are

summarized in Table 5. Temperature and paste pH profiles for test pits E10 through E170 are provided in Appendix 3.

TABLE 5

SURFACE TEMPERATURE AND pH ALONG E-E

| HOLE | TEMPERATURE AIR | SURFACE | CHANGE | PASTE pH SURFACE SAMPLES |
|---|---|---|---|---|
| E10 | 13.0 | 15.3 | + 2.3 | 2.5 |
| E30 | 13.1 | 15.1 | + 2.0 | 2.5 |
| E60 | 11.7 | 14.2 | + 2.5 | 2.7 |
| E80 | 11.5 | 12.4 | + 0.9 | 6.0 |
| E100 | 11.5 | 10.6 | - 0.9 | 6.2 |
| E120 | 10.5 | 11.6 | + 1.1 | 2.7 |
| E140 | 10.5 | 11.4 | + 0.9 | 3.0 |
| E160 | 10.3 | 11.6 | + 1.3 | 3.0 |
| E170 | 9.6 | 11.6 | + 2.0 | 2.6 |

Comparison of the ambient air and surface temperatures summarized in Table 5 indicated that the surface and air temperatures generally decreased from E10 (ie. from backdrain) towards E170 (near spray bar beach) with surface temperatures slightly warmer than the ambient air temperatures at most sites. This was the order in which the samples were taken suggesting that soil temperatures changes were primarily a function of ambient air temperature changes, the effects of which would decrease rapidly with depth. The air and surface solids temperature variations did not correlate directly and significantly to surface sample pH changes. Although samples E10, 30, and 60, with pH values less than pH 4 did exhibit temperatures greater than 14$^{o}$C, samples E120, 140, 160, and 170 (also at pH <4), exhibited temperatures of approximately 11.5.

The heat "sources" in the tailings are transient and include both ambient atmosphere and oxidation of sulphides. The heat capacity of the tailings materials will vary with moisture content and mineralogy (Nicholson, 1989). As shown in Table 5, the difference between the air and surface sample

temperatures was smaller for the wetter, siltier surface samples (E100 to E160) than in the sandier surface areas near the back drain (see also Photograph 2).

The depth/temperature and pH profiles of test pits along E-E again did not indicate a direct statistical correlation with pH. There was an overall decrease in soil temperatures with the most rapid decrease near surface. This time lag from surface downward would be due to surface heating, and the insulating effect of the soil, restricting effects of the heat source. The relationship of soil temperature to moisture content and mineralogy is shown graphically for one test pit in Figure 7 for Hole E160. These same two factors also affect the rate of acid generation and from this data the extent of acid generation versus the modifying effects of moisture and mineralogy cannot be determined.

## Paste Analyses

Samples were taken at intervals over the depth of each test pit for both paste and shake flask analyses. This section discusses the results of the paste analyses. Data are provided in Appendix 3. Paste pH profiles for the test pits are summarized in Figure 8. The profiles can broadly be described in three categories:

i) Continuous low pH values extending to a near neutral pH layer at depth. At several sites the acidic pH values (less than pH 4) extended as deep as 35 cm. These sites included A20 west and east, E10, E60, E140, and E170.

ii) Near surface pH values between 4 and 5, gradually increasing with depth to near neutral values. These sites included B30, C60, E80, and E100.

iii) Discontinuous pH profile with low pH bands alternating with near neutral values. These sites included E30, E120, and E160.

The deposition pattern significantly affected the layering and distribution of sands and silts within the tailings mass as described in the test pit logs. Descriptions of the visual appearance of the layers corresponded to the pH profiles. The low pH layers (less than pH 4) were

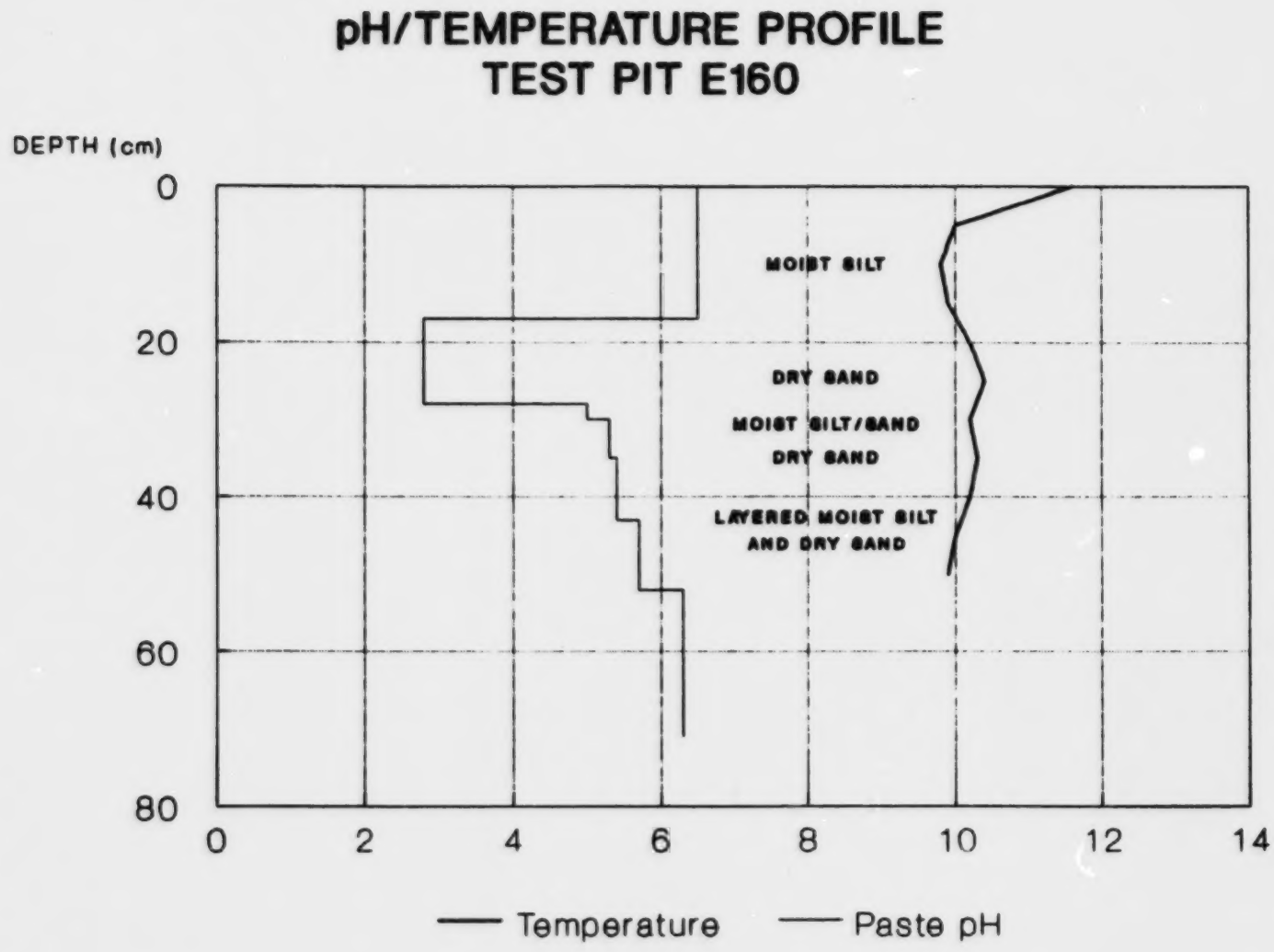



Figure 7 Depth Profile at Station E160.

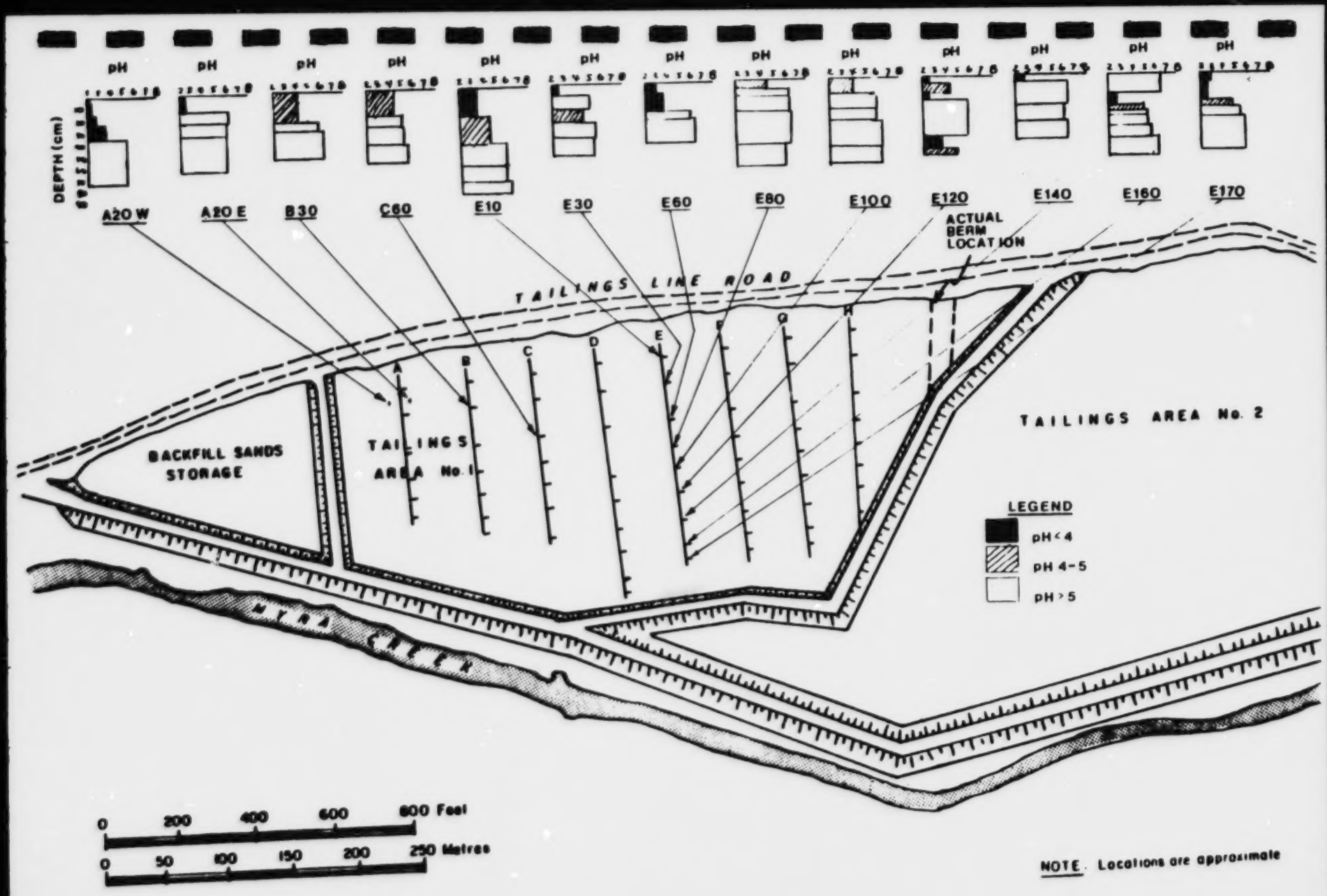



FIGURE 8 PASTE pH PROFILES - MAY 1988

generally orange/brown sands or orange/grey sand/silt layers. Layers with paste pH values greater than pH 4 were generally composed of moist grey or brown sands and wet grey silts. This pattern of layered tailings and pH values was particularly evident in the profile of E120.

The occurrence of low pH layers at depth might also be influenced by cracking of the tailings surface due to desiccation. The cracks expose surface area to oxygen and water, promoting oxidation at depth, and provide ready flow channels for the resultant acidic drainage. Site E120 was significantly fractured along the surface with cracks up to 2 cm in width, extending down to 40 cm depths. Orange coloration indicating surface oxidation was noted along the cracks.

The previous core sampling programme (1987) was limited in extent; five core paste pH profiles were derived (Figure 10 in Ferguson, 1987). These sites were not resampled in this test programme, however some comparisons were possible. Oxidation has continued in Area #1 in the twelve months since the last study as low pH zones extend to greater depth in 1988 compared to the 1987 study. Surface paste pH samples in areas with near neutral cores in 1987, also indicated that oxidation has occurred in the intervening 12 months. Alternating layers of low and high pH values were evident in 2 of the 1987 cores (C2 and C4).

Statistical analyses were conducted to determine if paste pH, total dissolved solids, and redox potentials of the test pit and surface samples could be related statistically with the following results:

i) test pit redox potentials and total dissolved solids of test pit samples did not correlate statistically however higher redox potentials (more oxidizing) generally corresponded to higher TDS,

ii) a similar analysis for the complete set of data (test pit and surface samples) again did not result in a mathematical relationship (correlation coefficient less than -0.68 for the equations tested),

iii) a comparison of paste pH and TDS for the complete data base again did not result in an R value greater than -0.67.

iv) paste pH and ORP values are related for specific redox couples (by definition). Analysis of the data suggests the relationship:

$$\ln(pH) = -1.71 \times \ln(ORP) + 13.3 \quad \text{with } R = -0.88$$

# PASTE pH versus NEUTRALIZATION POTENTIAL - AREA #1

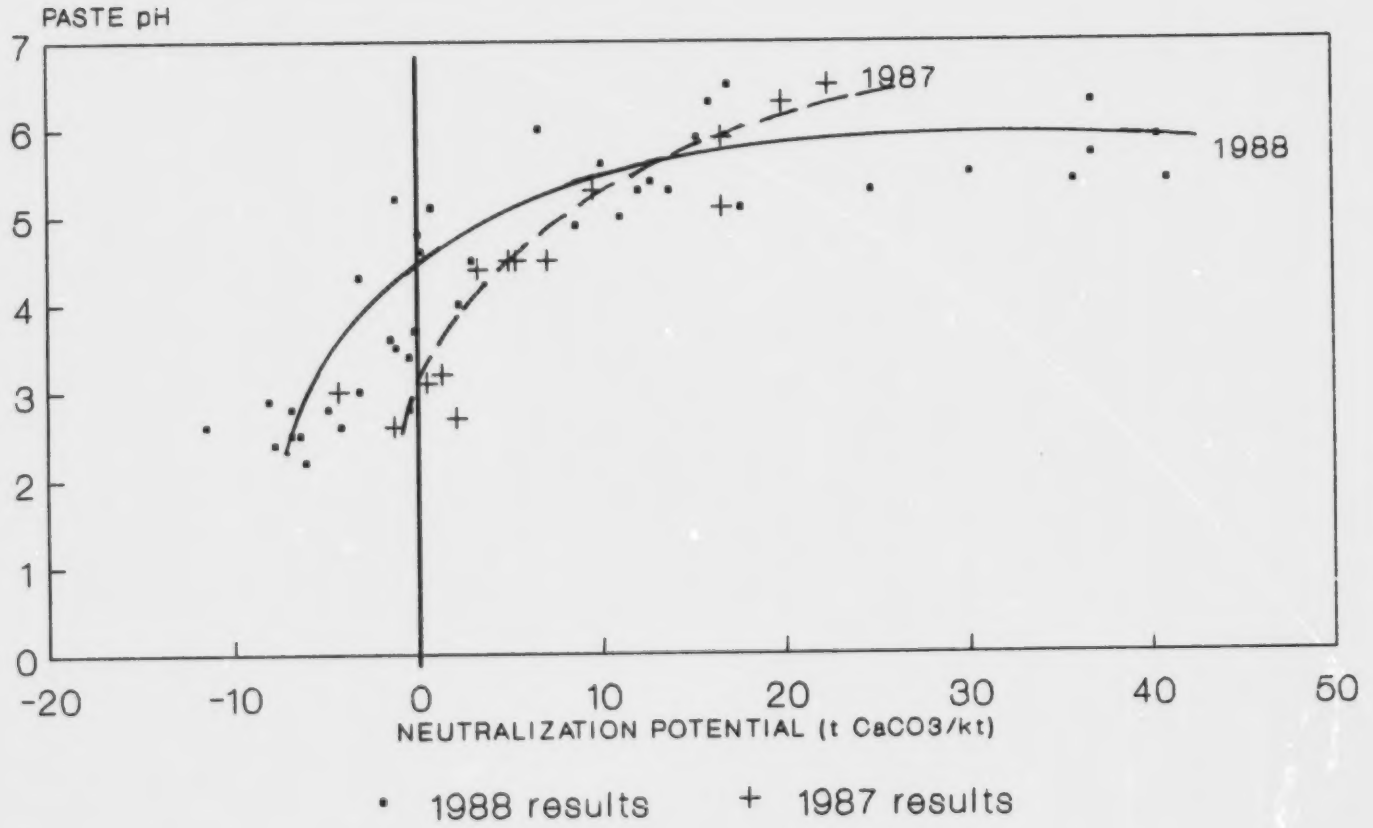



Figure 9 Relation of Paste pH and Neutralization Potential.

Paste pH and neutralization potential values were compared in Figure 9. In general, at pH values below 3.5 the neutralization potential has been depleted. At a pH value above 5, neutralization potentials varied from 0 to 40 t $CaCO_3$/1000 t. This suggests that acid was generated at different rates throughout the sampling area, and was buffered and consuming neutralization potential.

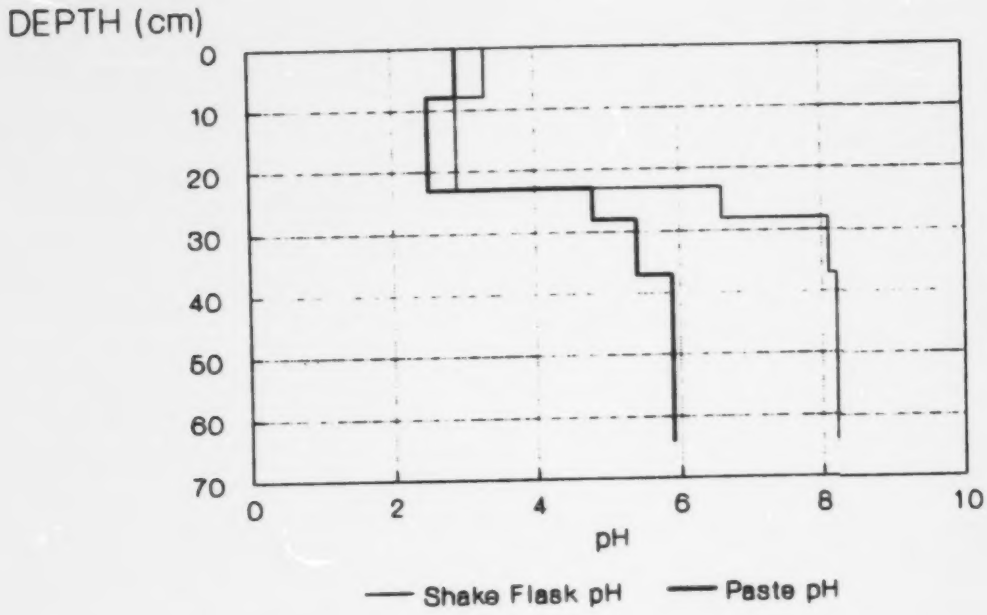
## Shake Flask Analyses

The results of the shake flask analyses, including data and graphical interpretations, are provided in Appendix 4. In the interpretation of shake flask results, it must be noted that these solution samples are not actual pore water samples. Pore water samples were not taken in this survey. Due to the shake flask procedure, these are very dilute solutions of the total soluble contaminants. Thus the following discussion is based on changes in concentrations in shake flask solution from the "fresh" samples from Area #2 (Table 2) to the older samples from Are #1.

The pH profiles derived for each test pit from shake flask tests were similar in trend to the paste pH results as shown in hole E170 and auger sample E160 (for example) in Figure 10. Shake flask pH values however were consistently higher, by 1 to 2 pH units, with the exception of isolated surface samples (E80, E100). The difference in the pH values between the two procedures could be due to the dilution of acidic pore water in the shake flask tests. It was not clear why some of the surface paste pH values were higher than the shake flask values.

Analyses of acidity, conductivity, sulphate, and dissolved copper, iron and zinc were also conducted on the test pit samples as part of the shake flask tests. The physical appearance and composition of each of the test pits can be useful in understanding the geochemical data, therefore the information from the shake flask analyses of the samples and the test pits logs were summarized in the following descriptions of each hole.

## COMPARISON OF PASTE AND SHAKE FLASK pH
## TEST PIT E170




## COMPARISON OF PASTE AND SHAKE FLASK pH
## AUGER SAMPLE E160

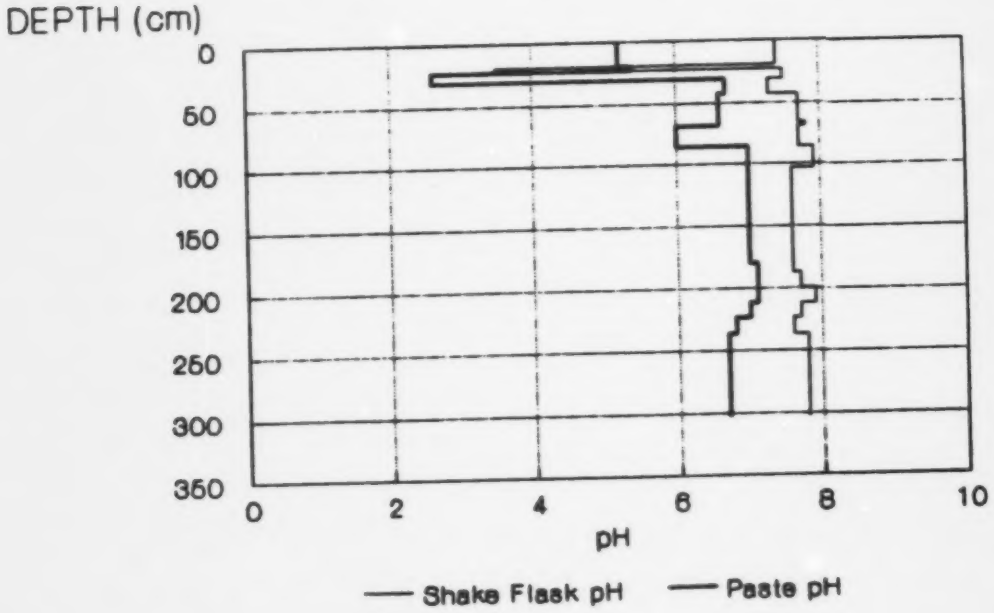



FIGURE 10

E10 An acidic surface layer extended down to 48 cm with pH gradually increasing over the depth of the hole. Copper and zinc levels were high in this upper layer with moderately high iron levels. The logs described orange coloration indicating metal oxide and hydroxide (iron) precipitation near surface. Zinc concentrations were high over entire column at greater than 10.9 mg/L. The pH, acidity, sulphate, and metal trends were comparable over depth with most acidic conditions noted in interval B (23 - 48 cm), an area described as silt grading down to moist grey sand.

E30 A shallow acidic surface layer extended down 9 cm to wet, grey silt with near neutral pH and low acidity. Elevated surface iron concentrations decreased rapidly at 20 cm depth. Bands of orange sand (oxidized) were noted down to 31 cm, which might be due to surface oxidation during deposition. Zinc concentrations peaked at 20 cm depth (35.7 mg/L) and gradually decreased over depth, although still represent elevated values. Sulphate and conductivity followed a similar pattern.

E60 The shallow low pH surface layer extended down through 8 cm of loose sand to dense sand, grey-brown and orange in colour throughout. This layer was less acidic than other layers of similar pH. Acidity, sulphate and conductivity decreased over depth as pH increases. Elevated copper levels were noted, particularly in interval B (23 cm depth). Iron levels were elevated in the surface layer but are very low below the surface layer. Zinc levels increased over depth with values comparable to the 3 to 6 month Area #2 samples.

E80 A shallow, low pH, acidic surface layer A extended down to layer B which consisted of wet, grey silt at neutral pH and low acidity. Sulphate and conductivity increased over greater depth than the low pH values with maxima at greater depth than the pH minimum. Iron, copper and zinc levels peaked in interval B (17 cm depth), decreasing beyond this depth in stages comparable to the 6 month fresh tailings of Area #2.

E100 The surface layer was acidic, increasing to neutral pH by 26 cm. The tailings material described as dry brown sand at surface grading to moist,

grey, sandy silt through top 30 cm. There was no description of orange coloration however elevated iron levels at surface were noted which decreased over depth, corresponding to the acidity, sulphate, conductivity, and metal profiles. Copper and zinc levels were slightly elevated at surface but decreased to low concentrations by 26 cm depth.

E120 The pH profile showed alternating layers of acidic and neutral pH. The acidity varied inversely with pH with very high acidity in the surface, low pH layer. Interval B at pH 6.7 had an unexpectedly high acidity value (233 mg/L). Low pH layers corresponded to grey/orange or brown layered sands or flaky/layered silts, whereas high pH layers corresponded to wet, grey, clayey silt. The neutralization potential was depleted in the upper 19 cm, and was negative in interval E (50 to 61 cm).

Metal concentrations varied over depth with some values as low as "fresh" tailings from Area #2. Metal distribution patterns can be affected by both the layering of the tailings and surface cracking causing the development of preferential flow paths of acidic drainage. Iron levels were very high at surface and high in layers C, and E, corresponding to low pH and high acidity. Copper levels were elevated at surface at 10 mg/L and decreased with depth until layer E where there was another peak of 9.3 mg/L. Zinc concentrations peaked in interval B at 182 mg/L and showed an increase with depth from 19 to 64 cm. Oxidation was noted along vertical cracks to 40 cm depth.

E140 There was a very shallow low pH surface with high acidity in orange/brown moist silt grading down to moist, grey silt. Sulphate concentrations showed a decrease slightly deeper than the increase in pH and decrease in metal concentrations. Metal levels were elevated, with very high iron levels at surface, and decreased to "fresh" tailings levels with depth.

E160 Neutral pH was noted over depth with the exception of layer B (17 to 28 cm). Layer B, consisting of dry orange/yellow fine sand, exhibited marked oxidation with low pH, high acidity, and elevated sulphate and metal levels. Conductivity, sulphate and zinc levels were also elevated in the top layer, A, from 0 to 17 cm. The neutralization potential for layer A of 16.9 tonnes

$CaCO_3$/1000 tonnes was somewhat depleted with respect to other layers of similar description (layer F at 36.8 t $CaCO_3$/kt).

E170 The acidic surface layer extended 23 cm deep to moist, grey, plastic silt of near neutral pH but relatively high acidity. Sulphate, conductivity, acidity and iron values corresponded inversely to the pH profile over depth. Zinc concentrations peaked at 28 cm depth, slightly deeper than the pH minimum and subsequently decreased with depth.

A20 West Acidic surface layer extended down 35 cm through primarily dry orange/brown sand with gradually increasing pH and less acidity. Surface iron levels were elevated, decreasing with depth to low levels. Sulphate, conductivity, copper and iron profiles were similar in shape with low surface levels which increased through to 40 cm in depth and then began to decrease (deeper than the point at which pH increased).

A20 East The pH profile was consistent at neutral pH, however elevated acidity, sulphate and conductivity levels were evident in layer B despite a pH value of 7.1. There was a high zinc concentration in layer B which consisted of moist, grey silt with an oxidized band.

B30 The slightly acidic surface layer extended down 28 cm through fine orange sand to sand interbedded with silt of neutral pH and low acidity. High sulphate and conductivity values occurred in the layer below the pH minimum. Copper and iron concentrations were slightly elevated in the acidic layer and decreased with depth and increased pH. Zinc values increased slightly with depth and were comparable to the 3 to 6 months samples of tailings from Area #2.

E160 Auger Extensive vertical and lateral cracking was recorded to a depth of 70 cm at the site E160 with oxidation noted along the exposed surfaces. Neutral pH values were recorded over the depth of the auger hole in the test pit with the exception of layer B, 18 to 23 cm deep, at pH 3.5 and corresponding acidity. Elevated sulphate and conductivity values were recorded from surface down to the 23 cm depth decreasing from there with depth

(erratically). Iron and copper concentrations were low, with the exception of layer B. Zinc levels however were elevated near surface and slowly decreased with depth.

## Comparison of fresh and subaerial tailings

The results of the shake flask tests conducted on the "fresh" tailings samples (SUB 1 to 3 as shown in Table 2) and the subaerial samples (as provided in Appendix 3) were compared to examine the changes that have occurred in various parameters indicative of acid generation and contaminant migration, over the 30 month deposition period. As these samples are dilute compared to pore water samples, changes over time, as opposed to absolute values are most useful to consider. The ratio of each parameter with respect to the fresh samples from Area #2 has been calculated and data are provided in Appendix 5. The change in pH over time is more clearly represented by difference between the fresh and 30 month samples and these data are presented below and summarized graphically in Figure 11. They are also included in the Appendix. The range of changes can be summarized:

| PARAMETER | INCREASE FROM FRESH VALUE |
|---|---|
| pH | Difference of 0 to 5.2 units |
| Acidity | 0 to 298 times fresh |
| Sulphate | 0 to 9.3 times fresh |
| Conductivity | 0.4 to 5 times fresh |
| Copper | 0 to 2,396 times fresh |
| Iron | 0 to 66,632 times fresh |
| Zinc | 0 to 248 times fresh |

Generally the data show that there have been significant changes in each of the parameters for different samples. The largest increases in concentration and decreases in pH were evident in samples within 30 cm of surface, although many near surface samples showed little or no change. There were some test pit areas which showed marked changes in some parameters at depth. Typically these were test pit areas with deep penetration of low pH and/or contaminant fronts, and areas of surface cracking.

# FRESH vs 30 MONTH SUBAERIAL TAILINGS DIFFERENCE AS A FUNCTION OF DEPTH

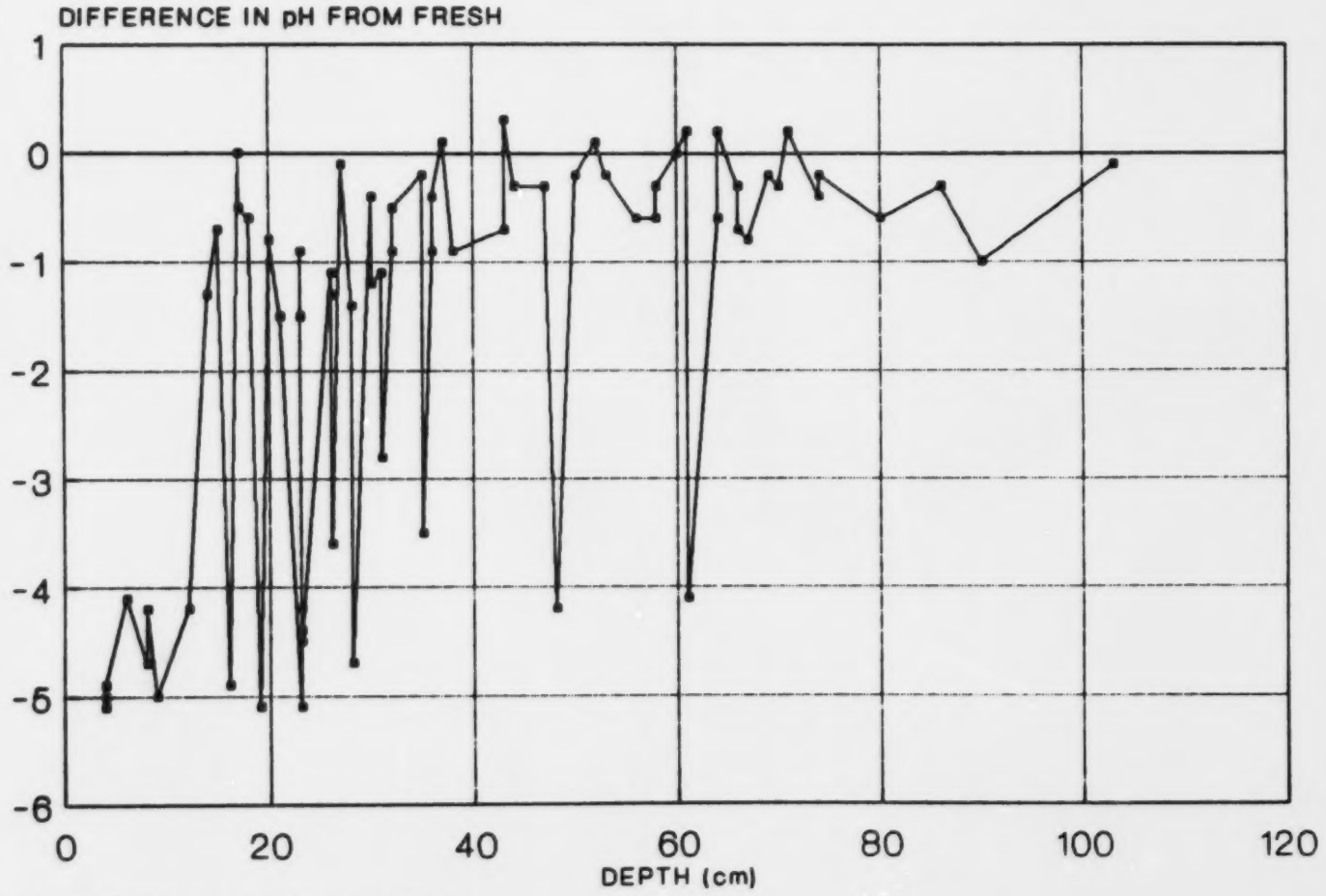



Figure 11 Change in pH over time.

Generally, the change in pH was larger for shallow samples than for samples at depth. There were two apparently anomalous samples at depth which showed a marked decrease in pH occur at E10 and E120. As shown in Tables 6 and 7, the contaminant fronts have penetrated to greater depth in both these test pits. Sample E120 was also in an area of surface cracking.

Similar results were evident for increases in acidity, sulphate, and conductivity with the most significant changes in values evident in the more shallow samples (less than 30 cm). Some very large changes were evident for sulphate, acidity, and conductivity at E10 interval B, and E120 interval E and F, which might be caused by surface cracking and drainage patterns.

The degree of change in copper concentrations did not appear to be a function of depth. Test pit E10 again showed a large change in copper concentration over time at interval B, almost 2400 times the concentration from a fresh sample. At holes E60 and E80 interval B, large increases in copper concentration were also evident. The most significant changes in iron values were evident in approximately half of the samples within 30 cm of surface, with deeper samples showing little or no change. Similar observations can also be made of the changes in zinc concentration after 30 months of exposure however increased concentrations were evident over greater depths than for copper and iron. The largest changes were evident in shallow samples, with a few large increases in layers at depth, similar to other contaminants, noted for holes E10 interval B, and E120 interval F.

TABLE 6

SUMMARY OF SHAKE FLASK RESULTS
DEPTH OF CONTAMINANT FRONTS

| HOLE | DEPTH TO CONTAMINANT FRONTS (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | pH | Acidity | Sulphate | Conductivity | Dissolved Metals Cu | Fe | Zn |
| E-10 | 48 | 90 p | 80 | 48 | 48 | | 90 p |
| E-30 | 31 v | 44 | 31 v | 31 v | 31 v | 9 | 60 p |
| E-60 | 8 | 50 p | 30 | 23 | 30 | 8 | 50 p |
| E-80 | 6 | 26 | 26 v | 0 | 17 v | 17 v | 56 |
| E-100 | 12 | 36 | 58 | 26 | 12 | 12 | 58 |
| E-120 | 61 v | 64 vp | 64 vp | 64 vp | 61 v | 61 v | 64 vp |
| E-140 | 4 | 38 v | 27 | 27 | 4 | 4 | 53 p |
| E-160 | 28 v | 35 | 28 | 28 | 28 v | 28 v | 35 |
| E160deep | 23 v | 43 | 69 v | 23 | 23 v | 23 v | 43 |
| E-170 | 23 | 28 | 28 | 28 | 28 | 23 | 28 |
| A-20west | 35 | 35 | 35 v | 35 v | 35 v | 35 | 74 vp |
| A-20east | 0 | 36 v | 36 v | 23 v | 0 | 0 | 66 p |
| B-30 | 26 | 58 | 32 v | 0 | 32 | 26 | 58 p |
| C-60 | 0 | 47 | 31 v | 31 v | 31 | 0 | 61 p |

NOTES: v - variable pattern over depth interval
p - contaminant above criteria at maximum depth of hole

CRITERIA: pH difference > 2 pH units
Acidity difference > 10 mg/L
Sulphate difference > 300 mg/L
Conductivity difference > 600 mg/L
Copper difference > 1 mg/L
Iron difference > 1 mg/L
Zinc difference > 3 mg/L

## TABLE 7

## RELATIVE POSITION OF CONTAMINANT FRONTS

| ORDERING BASED ON CONTAMINANT FRONTS: | | | |
|---|---|---|---|
| All fronts | Zinc and Acidity: | Sulphate and Conductivity | pH, Cu, Fe |
| Deepest | | | |
| E-10 | E-10 | E-10 | E-120 |
| E-120 | E-120 | E-120 | E-10 |
| A-20 west | B-30 | E-160 deep | A-20 west |
| E-160deep | A-20 west | E-100 | E-160 |
| E-30 | C-60 | A-20 west | B-30 |
| B-30 | E-30 | C-60 | E-170 |
| E-100 | A-20 east | E-30 | E-30 |
| E-160 | E-60 | A-20 east | E-160 deep |
| C-60 | E-100 | E-160 | E-60 |
| E-60 | E-140 | E-170 | E-80 |
| E-170 | E-160 deep | E-140 | E-100 |
| A-20 east | E-80 | E-60 | C-60 |
| E-140 | E-160 | B-30 | E-140 |
| E-80 | E-170 | E-80 | A-20 east |
| Shallowest | | | |

## Contaminant Fronts

To determine the progression of acid generation and the flow patterns of the acid drainage and its characteristic contaminants, graphs were plotted of the locations of various fronts including pH, acidity, sulphate, conductivity, and dissolved metals. The location of each front was determined using shake flask test results for fresh (from Area #2) and 30 month old tailings samples. The analyses of the fresh tailings sample were used as the background values for each parameter. The difference between the background value, and the reading after 30 months of deposition, was calculated (as above) at each interval to determine where elevated levels of the parameters existed.

The determination of an "elevated level" which would indicate a significant change over time in any parameter was primarily an empirical decision based on the fresh (Area #2) and 30 month (Area #1) samples. Acidity values greater than 10 mg/L were considered to be high, and over 100 mg/L to be very high. Sulphate levels varied significantly with the nature of the tailings material; for these samples, with a background value of 140 mg/L, 300 mg/L was considered to be high. Baseline conductivity levels were 430 mg/L with Area #1 values ranging up to 2150 mg/l. Metal concentrations in excess of 1 mg/L were considered elevated in a tailings solution. The following criteria were then established to identify the position of each contaminant front by considering these values, and the range of differences calculated for each parameter. A difference larger than the values listed below was considered to indicate that a significant change had occurred at that sample location due to acid generation at that location, and/or the vertical transport of acid drainage (by advection, diffusion and dispersion) to that position.

| Parameter | Difference of: |
|---|---|
| pH | > 2 pH units |
| acidity | > 10 mg/L |
| sulphate | > 300 mg/L |
| conductivity | > 600 mg/L |
| copper | > 1 mg/L |
| iron | > 1 mg/L |
| zinc | > 3 mg/L |

The depth of the front in each test pit in Area #1 (as summarized in Table 6) was plotted as shown for example in Figure 12a, showing pH and acidity fronts. Similar plots for each parameter are provided in Appendix 6. The depths of the contaminant fronts were also plotted on the fence diagrams as shown in Figures 12b and 12c. The layered heterogeneity in the tailings mass has been noted throughout this study, and holes in which variable patterns were evident over the depth interval, and those in which the contaminant plumes continue below the samples, are noted on the graphs.

The concentration and distribution of each contaminant is dependent on a number of factors:

i) source configuration, ie. depth and area over which acid is generated,

ii) groundwater flow rate and vertical and horizonal components of flow

iii) order and rate of generation of each front

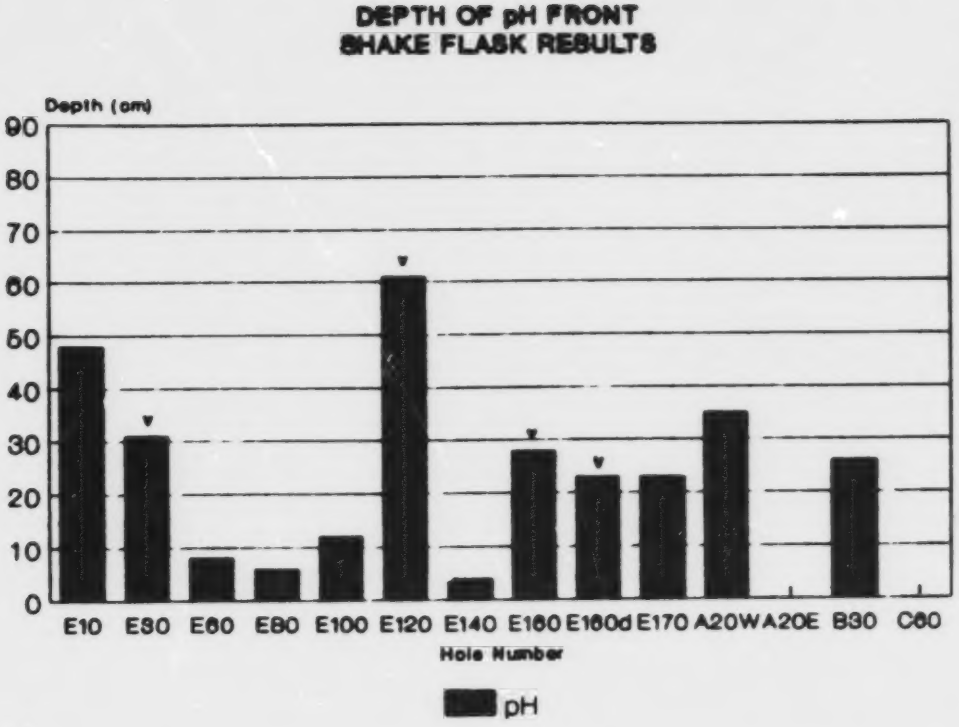
iv) retardation reactions (particularly affected by pH)

v) diffusion and dispersion effects in each layer

Thus the positions of the fronts indicate both the order and rate at which each contaminant is generated, and the relative mobility of each front under the given conditions. Insufficient information was available to differentiate the two effects. The position of the oxidation front is more difficult to establish without more information on the drainage patterns in the tailings mass. Both the solution chemistry and hydrology of the tailings mass can be very complex.

The data and the graphs indicated that the zinc and acidity fronts seemed to be the first generated and/or the most mobile, occurring deeper than the other fronts in most test pits. These two fronts occurred at the same depth in at least 50 % of the holes.

Sulphate and conductivity fronts also appeared to be related occurring at the same depth in 50 % of the holes, and generally shallower than zinc and acidity fronts. These two parameters are often used in the estimation of advective groundwater velocity in contamination situations due to their conservative behaviour (relatively non-reactive). Sulphate ions are probably


DEPTH OF pH FRONT
SHAKE FLASK RESULTS
Depth (cm)
90
80
70
60
50
40
30
20
10
0
E10 E30 E60 E80 E100 E120 E140 E160 E160d E170 A20W A20E B30 C60
Hole Number
pH

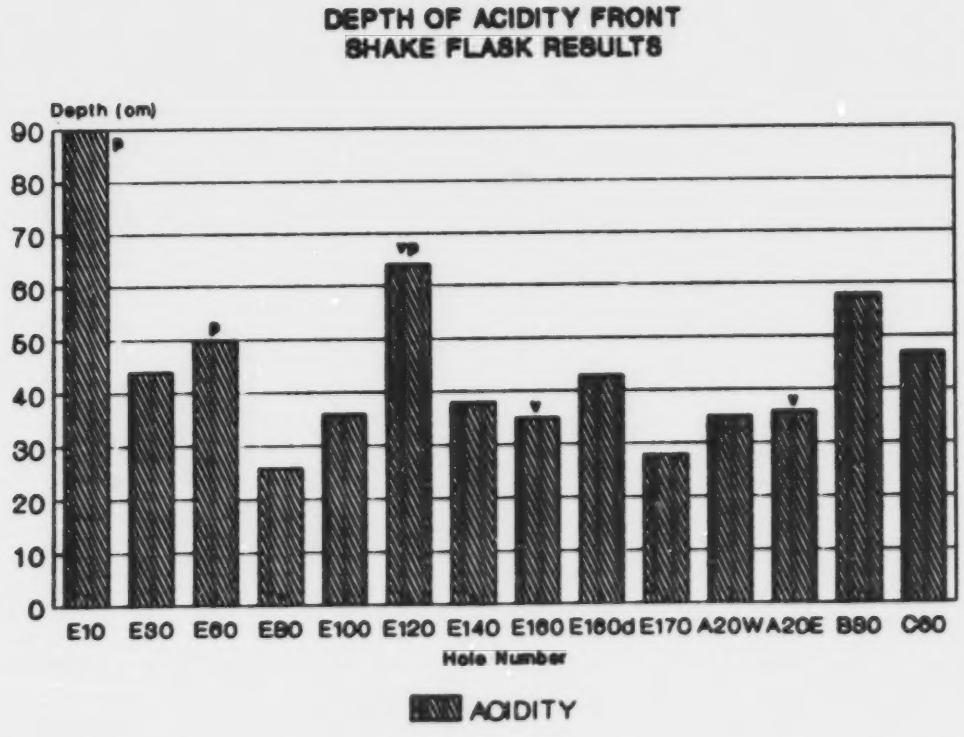

DEPTH OF ACIDITY FRONT
SHAKE FLASK RESULTS
Depth (cm)
90
80
70
60
50
40
30
20
10
0
E10 E30 E60 E80 E100 E120 E140 E160 E160d E170 A20W A20E B30 C60
Hole Number
ACIDITY

FIGURE 12a

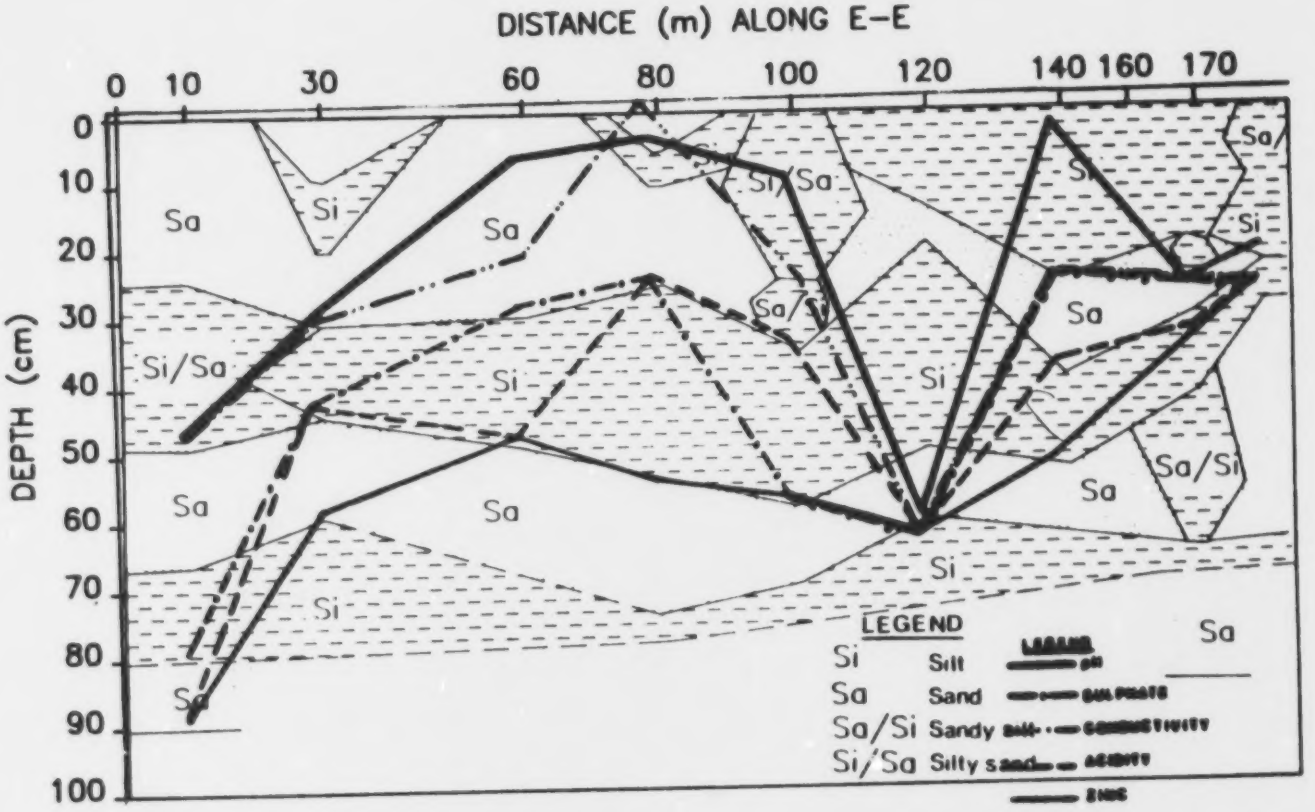



FIGURE 12b DEPTH PROFILE ALONG LINE E-E - AREA 1

WITH OVERLAY OF CONTAMINANT FRONTS

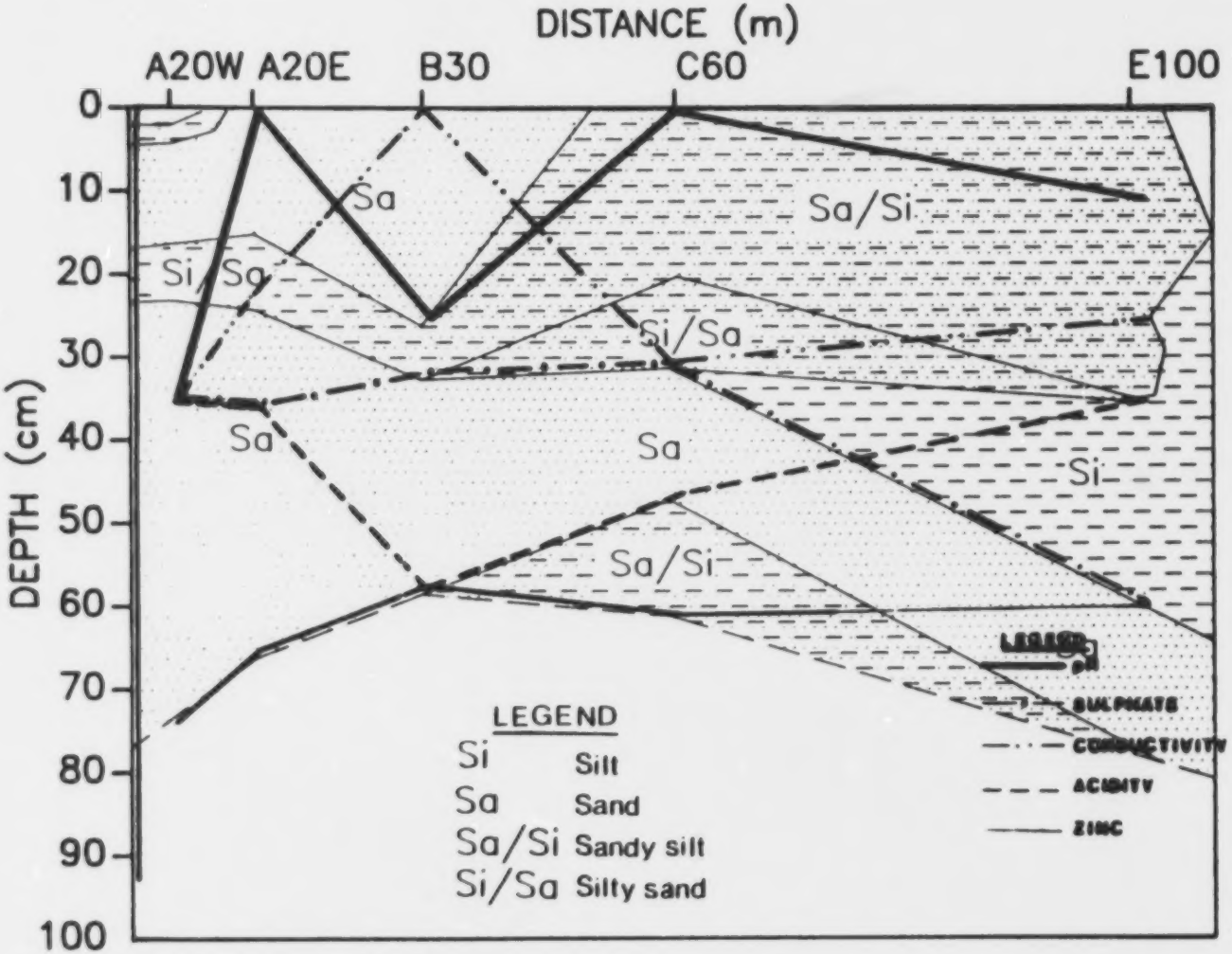



FIGURE 12c DEPTH PROFILE FROM A20 TO E100 - AREA 1
WITH OVERLAY OF CONTAMINANT FRONTS

the dominant anion and would therefore contribute significantly to conductivity; this would explain the correlation of the sulphate and conductivity fronts.

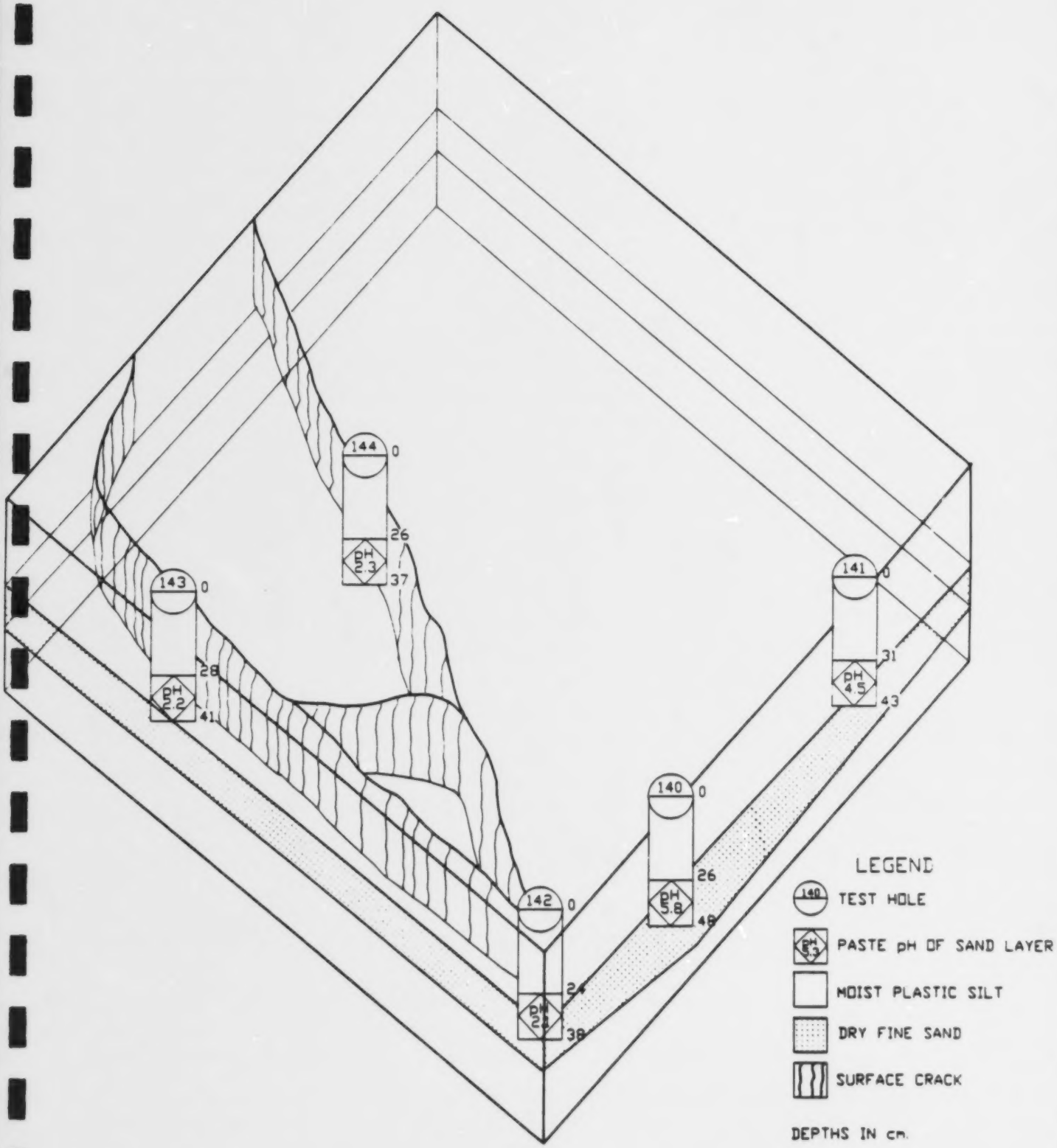
The shallowest fronts were those of pH, copper and iron. This pattern is reasonable as copper and iron require low pH environments for mobility. Oxide and hydroxide precipitation reactions inhibit metal mobility in alkaline conditions.

The extent of the penetration of acid drainage in the tailings mass of Area #1 along E-E can be expressed using these pairs or triplets of contaminant fronts. Table 7 summarizes the depth to which each has penetrated by ordering the holes. The positions of these fronts, is considered in more detail in light of the geotechnical characteristics of the samples, Sections 3.3 and 3.4.

## Crack Effects

Detailed sampling was conducted around the cracks at station E140. The configuration of the cracks, which extended down to a sand layer, and the paste pH analyses are shown in Figure 13. Samples 140 and 141 were taken in the sand layer at some distance from the cracks and report paste pH values of 5.8 and 4.5 respectively. Samples 142, 143, and 144 were also taken from the sand layer, but at the base of a crack from surface. Acidic paste pH values were noted for each of these samples, indicating the transfer of oxygen and water (including acidic drainage from near surface) along the cracks, promoting oxidation at depth.

Results of the shake flask extractions on these samples are summarized in Table 8. The effects of the cracking and increased acid generation due to oxygen and water transfer along the crack were again evident in the data; samples 140 and 141 had pH values of 6.9 and 4.3 respectively, while 142, 143, and 144 averaged pH 3.0. Samples at distance from the crack area had lower acidity, conductivity, sulphate and iron values than the three samples along the crack. Zinc levels approximated fresh tailings (at 5.5 mg/L) in sample 140 but were elevated in all other samples. Copper levels were low in 140 and elevated in all other samples.




BLOCK DIAGRAM OF NEAR SURFACE CONDITIONS AROUND STATION E140

**FIGURE 13**

TABLE 8

SUMMARY OF SHAKE FLASK DATA
SAND SAMPLES FROM AROUND E140

| SAMPLE / PARAMETER * | | 140 | 141 | 142 | 143 | 144 |
|---|---|---|---|---|---|---|
| Acidity | | 3.50 | 53.9 | 312 | - | 377 |
| Alkalinity | | 12.0 | 1.0 | < 1.0 | < 1.0 | 1.0 |
| Conductivity | | 780 | 1050 | 1850 | 2150 | 1550 |
| Diss. Metals | | | | | | |
| ICP | Ag | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Al | < 0.05 | 0.51 | 6.07 | 38.66 | 8.07 |
| | As | < 0.05 | 0.05 | < 0.05 | < 0.05 | < 0.05 |
| | B | < 0.01 | 0.02 | 0.05 | 0.1 | 0.04 |
| | Ba | 0.128 | 0.136 | 0.138 | 0.115 | 0.143 |
| | Be | <0.001 | 0.001 | <0.001 | <0.001 | <0.001 |
| | Ca | 183 | 242 | 380 | 233.3 | 223 |
| | Cd | 0.087 | 0.164 | 0.14 | 0.068 | 0.068 |
| | Co | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| | Cr | <0.005 | <0.005 | 0.043 | 0.11 | 0.037 |
| | Cu | 0.043 | 5.61 | 10.6 | 5.75 | 7.03 |
| | Fe | 0.221 | 1.14 | 100 | 703.3 | 131 |
| | Mg | 3 | 8.9 | 3.4 | 34.83 | 5.8 |
| | Mn | 2.04 | 1.48 | 0.289 | 1.063 | 0.317 |
| | Mo | < 0.01 | < 0.01 | < 0.01 | < 0.01 | < 0.01 |
| | Na | 1.0 | 1.3 | 1.4 | 3.3 | 1.5 |
| | Ni | < 0.02 | 0.02 | 0.02 | 0.116 | 0.04 |
| | P | < 0.1 | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| | Pb | < 0.05 | 2.35 | 2.2 | 3.233 | 2.33 |
| | Sb | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| | Se | < 0.05 | < 0.05 | 0.08 | 0.65 | 0.16 |
| | Si | 0.23 | 0.74 | 0.83 | 3.35 | 1.34 |
| | Sn | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| | Sr | 0.286 | 0.166 | 0.277 | 0.235 | 0.114 |
| | Ti | <0.002 | <0.002 | 0.003 | 0.003 | <0.002 |
| | V | < 0.01 | < 0.01 | < 0.01 | 0.05 | < 0.01 |
| | Zn | 5.51 | 25.2 | 34.7 | 23.66 | 15.9 |
| Hardness (Ca + Mg) | | 470 | 641 | 963 | 437 | 582 |
| Hardness (Total) | | 483 | 688 | 1230 | 1340 | 886 |
| pH | | 6.9 | 4.3 | 3.2 | 2.9 | 3.1 |
| Sulphate | | 380 | 530 | 1100 | 1300 | 870 |
| Turbidity | | 0.1 | < 0.1 | < 0.1 | 0.2 | < 0.1 |

* all units mg/L except conductivity - umhos/cm, pH - pH units, turbidity - FTU

### 3.3.2 Geotechnical

Fractional analyses were conducted on surface and depth samples along E-E and are provided in Appendix 7. The measured sand/silt/clay distributions generally corresponded well with the log descriptions of each layer. The most significant discrepancy was noted between the log descriptions and geotechnical analyses of samples E60 and E140. All of the comparisons and calculations in the following sections of this report seemed to suggest that these two samples were mislabelled prior to testing. Fractional analyses showed the surface sample at E60 was silty (82 % silt) rather than sand as logged. Surface sample E140 was primarily sand with less silt than logged although descriptions by field personnel, and site photographs showed the surface of this area to be very silty. Thus for this report, the two samples have been relabelled as appears appropriate. Discrepancies between the logs and the fractional analyses could also be due in part to the inherent difficulties in sampling heterogeneous material.

The complete results of the geotechnical analyses are detailed in Appendix 6 and summarized in Tables 9 and 10. In general, the surface tailings samples could be described in two groups. Samples near the centre of the impoundment and one near the subaerial spray bar beach (E160) were primarily silts with some sand and clay. These samples were near 100 % saturation, and roughly correspond to the siltier, wetter areas visible in Photograph 2. Samples with a higher sand content (> 60 % sand) were less than 70 % saturated and corresponded to drier areas in the photograph.

Geotechnical parameters were also evaluated for depth samples along E-E. These samples were selected for analysis to evaluate the effect of geotechnical parameters on the progression of acid generation and drainage. The specific gravity of the tailings material was estimated at 3.61, from the results of the 1987 study. Saturated hydraulic conductivity values were calculated from the grain size analyses using the Hazen equation.

The position of the groups of contaminant fronts will be determined to a large extent by the geotechnical characteristics of the tailings mass. The results of the geotechnical analyses of each hole are summarized below, and related to the contaminant fronts.

TABLE 9

RESULTS OF GEOTECHNICAL ANALYSES

SURFACE SAMPLES

| HOLE | | E10 | E30 | E60 | E80 | E100 | E120 | E140 | E160 | E170 |
|---|---|---|---|---|---|---|---|---|---|---|
| INTERVAL | cm | 0-11.5 | 0-11.2 | 0-13.0 | 0-11.5 | 0-11.5 | 0-11.5 | 0-14.3 | 0-17.4 | 0-19.1 |
| PARAMETER | | | | | | | | | | |
| Wet Density | kg/L | 1.93 | 2.07 | 2.14 | 2.22 | 2.26 | 2.04 | 2.27 | 2.01 | 2.10 |
| Dry Density | kg/L | 1.65 | 1.66 | 1.78 | 1.78 | 1.82 | 1.63 | 1.80 | 1.47 | 1.79 |
| Water Content | | 0.17 | 0.25 | 0.20 | 0.25 | 0.24 | 0.25 | 0.26 | 0.36 | 0.18 |
| Void Ratio | | 1.19 | 1.17 | 1.02 | 1.03 | 0.98 | 1.21 | 1.00 | 1.45 | 1.02 |
| Porosity | | 0.54 | 0.54 | 0.51 | 0.51 | 0.50 | 0.55 | 0.50 | 0.59 | 0.51 |
| Degree of Saturation | | 0.52 | 0.76 | 0.70 | 0.87 | 0.88 | 0.75 | 0.94 | 0.90 | 0.62 |
| Hydraulic Conductivity | (m/s) | $9\times10^{-6}$ | $3.6\times10^{-7}$ | $2.5\times10^{-5}$ | $9\times10^{-8}$ | $1.2\times10^{-7}$ | $4\times10^{-8}$ | $4\times10^{-8}$ | $1\times10^{-6}$ | $2\times10^{-7}$ |
| Specific Gravity | | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 |
| Particle Size | % | | | | | | | | | |
| Sand | | 72 | 33 | 80 | 23 | 26 | 10 | 10 | 7 | 63 |
| Silt | | 24 | 62 | 19 | 71 | 68 | 82 | 82 | 88 | 32 |
| Clay | | 4 | 5 | 1 | 6 | 6 | 8 | 8 | 5 | 5 |

# TABLE 10

## RESULTS OF GEOTECHNICAL ANALYSES

### DEPTH SAMPLES

| HOLE | | E10 | E30 | E80 | E100 | E120 | E140 | E140 | E170 |
|---|---|---|---|---|---|---|---|---|---|
| INTERVAL | cm | 34.7-43.3 | 19.5-29.5 | 38.6-45.4 | 39.7-48.3 | 23.7-32.3 | 14.4-25.6 | 30.7-39.3 | 12.2-23.8 |
| PARAMETER | | | | | | | | | |
| Wet Density | kg/L | 2.11 | 2.14 | 2.30 | 1.78 | 1.82 | 1.74 | 2.01 | 2.27 |
| Dry Density | kg/L | 1.81 | 1.81 | 1.85 | 1.34 | 1.39 | 1.21 | 1.79 | 1.93 |
| Water Content | | 0.17 | 0.18 | 0.24 | 0.33 | 0.31 | 0.44 | 0.12 | 0.18 |
| Void Ratio | | 1.00 | 0.99 | 0.95 | 1.70 | 1.60 | 1.99 | 1.01 | 0.87 |
| Porosity | | 0.50 | 0.50 | 0.49 | 0.63 | 0.62 | 0.67 | 0.50 | 0.47 |
| Degree of Saturation | | 0.60 | 0.65 | 0.92 | 0.70 | 0.70 | 0.80 | 0.43 | 0.73 |
| Hydraulic Conductivity | (m/s) | $1.6\times10^{-5}$ | $9.0\times10^{-6}$ | $9\times10^{-8}$ | $4\times10^{-8}$ | $2.3\times10^{-8}$ | $1\times10^{-8}$ | $1.2\times10^{-5}$ | $6.3\times10^{-6}$ |
| Specific Gravity | | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 | 3.61 |
| Particle Size | % | | | | | | | | |
| Sand | | 81 | 72 | 24 | 37 | 11 | 1 | 72 | 68 |
| Silt | | 16 | 23 | 70 | 55 | 80 | 84 | 25 | 27 |
| Clay | | 3 | 5 | 6 | 8 | 9 | 15 | 3 | 5 |

E10 The sample logs and fence diagram showed this test pit had a high sand and sandy silt content. This was reflected in the hydraulic conductivity of the surface and depth samples ($10^{-4}$ and $10^{-3}$ cm/s respectively) and low porosity, close to the designed porosity for the HW material. The tailings were well drained at the surface with a degree of saturation of 50 % at surface and 60 % at depth. The zinc, acidity and sulphate fronts have penetrated deep into the mass, and the conductivity, pH, copper and iron fronts have penetrated about half as far (through the silt/sand layer).

E30 Alternate layers of sand and silt predominated over depth. The surface sample was primarily silt at 76 % saturation and conductivity of $3.6 \times 10^{-5}$ cm/s. The sample at depth was taken in a sand layer (just below a silt layer) and was less saturated (65 %) and more permeable than at surface. The progression of the contaminant fronts appeared to have been limited to some extent with most fronts located between 30 and 40 cm depth. The iron front however extended only to 9 cm, coinciding with the beginning of silty material. The zinc front appeared most mobile, extending to 60 cm in depth.

E60 The surface sample fractional analysis showed 80 % sand content and little clay. At 70 % degree of saturation, and relatively high conductivity ($2.5 \times 10^{-3}$ cm/s) the sample tested was characteristic of a sand. Samples were not tested at depth, however the log indicated high silt content below 30 cm depth. The zinc and acidity fronts have penetrated to 50 cm depth (maximum depth recorded). The sulphate, conductivity, and copper fronts were located within the silt band between 23 and 30 cm. The pH and Fe fronts were significantly retarded, occurring at a depth of 8 cm.

E80 This profile was similar to that of E60 with alternating layers of silts and sands. Fractional analysis of the surface sample indicated 71 % silt which corresponded to the log description of silt with interbedded sand in the uppermost 4 cm. The depth sample had a similar composition. The two samples were close to 90 % saturation and had very low hydraulic conductivity ($10^{-6}$ cm/s). The contaminant fronts were relatively shallow, with the exception of the zinc front which had penetrated through the lower silt band (56 cm).

E100 The profile at this site was very similar to E80 with a wet, silty/sand surface layer of low permeability ($10^{-5}$ cm/s). The depth sample was also a slightly more permeable silty sand than E80, with a degree of saturation of 70 %. The fronts have progressed somewhat deeper with zinc and sulphate fronts extending through the lower silt band. The pH/Cu/Fe fronts were located at the lower edge of the upper silt band.

E120 The surface and depth samples at this site were silt samples with 8-9 % clay, and low permeability, although lower saturation at 75 % and 70 % for surface and depth respectively. Vertical cracking was noted at this site, and could explain the quite uniform progression of all fronts to the bottom of the hole. Alternate layering of sands and silts was noted over the depth of this hole, and similar layering of low and high paste pH values was evident as shown in Figure 8.

E140 Log descriptions and photographs at this site suggested the surface was primarily wet silt and fractional analyses indicated 82 % silt. Geotechnical parameters were also typical of silts; poorly drained with a degree of saturation of 94 %, hydraulic conductivity of $4 \times 10^{-6}$ cm/s and 8 % clay content. The position of the pH/Cu/Fe fronts was limited to shallow depth (4 cm).

Two samples were taken at depth at this site; one occurring in a shallow silty layer, the other between 30 and 39 cm in a sand layer. The geotechnical parameters were typical of such materials in the tailings area; the silt layer being more saturated, porous and less permeable than the sand layer. The sand layer had a very low water content at 43 % saturation. The zinc contaminant front was very mobile and extended through to the maximum depth of the hole.

E160 Surface material at this station was a wet silt, slightly more porous and permeable (at $K=10^{-4}$ cm/s) than silts elsewhere in Area #1. Samples were not tested at depth for geotechnical parameters, however the log indicated extensive layering in the test pit. The fronts have progressed quite uniformly with the zinc and acidity slightly deeper at 35 cm than the others at 28 cm. These fronts have penetrated through 25 cm of silt into a sand layer.

E170 Closest to the spray bar beach, this test pit was again layered but with primarily sands and sandy silts. The surface was a moderately permeable (2 x $10^{-5}$ cm/s) sand/silt at moderate saturation (62 %). The sample at depth was taken in a sand layer with some silt, and had a low porosity of 47 % and conductivity of 6 x $10^{-4}$ cm/s. Occurrence of the contaminant fronts was quite uniform near the lower extent of a silt layer at 28 cm depth.

The previous geotechnical sampling programme (1987) was conducted closer to the spigot discharge and found tailings which were either predominantly silts or roughly equal parts sand and silt. Similar trends were found in terms of sandier samples being less saturated and more permeable than siltier materials. Calculated conductivity values of silt samples were slightly higher in this survey at $10^{-6}$ cm/s.

### 3.3.3 Summary

Diagrams were constructed from the test pit logs to show the profiles of soil types along lines E-E, and from A to E. The layered heterogeneous nature of the tailings was evident in these diagrams, with layers varying from sands to silts as designed. The layers however did not appear to be continuous across the impoundment. In the upper 30 cm of the tailings, zones of sand, silt and silt/sand mixes are noted and layering was not well defined. Between approximately 30 and 50 cm, and deeper than 70 cm, silty material predominated, with a sandy layer between, from approximately 50 to 70 cm.

Temperature measurements seemed to vary primarily with material type (ie. sand or silt) and moisture content, and did not provide a direct indication of oxidation in the tailings. It is difficult to isolate the effects of moisture content from exothermic oxidation reactions on soil temperatures as the degree of oxidation (as indicated by paste pH and test pit log descriptions) also varied with the type of tailings material. Less evidence of oxidation, and lower temperatures were shown in silt material than in drier sandy material. Dry sandy materials generally respond more rapidly to external temperature changes than tailings with a higher moisture content.

The paste pH profiles over depth again demonstrated the layered nature of the tailings. Two main patterns were evident; many of the cores showed lower surface pH (from pH 2 to 5), with increases to near neutral pH values at

variable depths, or a pattern of alternating layers of low and near neutral pH. These alternating layers could be created by both the layered nature of the tailings, and the formation of surface cracks (due to desiccation) which promoted the transport of oxygen, water and acidic drainage to depth. Evidence of oxidation was noted in orange coloration of many of the sandy layers with correspondingly low pH values, less than pH 4. Higher pH layers tended to consist of grey/brown silts and sands. Neutralization potentials were lower than in the 1987 survey, and were depleted for all samples at less than pH 3.5.

Measurements of pH for samples from the test pits were done by both paste and shake flask analyses. The profiles were very similar in shape, however shake flask pH values were generally slightly higher than the paste values, due probably to the dilution of acidic pore water in the shake flask procedure.

Analyses of acidity, conductivity, sulphate, and dissolved copper, iron and zinc were also conducted on the test pit samples as part of the shake flask tests. The results were summarized with the descriptions of the test pit logs; the physical appearance and composition of each of the test pits can be useful in understanding these geochemical data. No direct correlations between contaminant concentrations and various layers within the tailings was evident however some comparisons were made. Generally dissolved copper and iron concentrations were highest in the lower pH layers near the surface of the tailings (within the top 30 cm). Orange/brown coloration from the precipitation of iron oxides and hydroxides was typically described in the logs for sand layers with high iron values, but not necessarily silt layers (E100). Elevated zinc concentrations were evident over greater depth. High concentrations of most contaminants were evident at depth in holes E10, which was primarily sand over depth, and hole E120, which was located in an area of considerable surface cracking. This cracking was more pronounced in the silt layers than in sands. Oxidation was noted along the exposed surfaces of vertical and lateral cracks, such as described in E160.

The locations of the contaminant fronts were determined by comparison of the shake flask data on test pit samples, with similar data for "fresh" tailings. Criteria were established from the empirical data to determine "elevated" concentrations which would indicate that acidic drainage was

present at that sampling depth. Groupings of contaminant fronts were located, although the depths at which these fronts appeared varied significantly across the sampling line. Generally zinc and acidity fronts were most mobile and/or generated most rapidly in the oxidation process and have penetrated to greatest depth in the impoundment. Sulphate ions were probably the dominant anions and contributed significantly to conductivity, and these two fronts appeared at similar depths in many test pits. Copper, iron and pH fronts were generally shallowest, which was reasonable as copper and iron require low pH environments for mobility.

Geotechnical analyses of test pit samples again demonstrated the layered heterogeneity of the tailings. The degree of saturation varied from 43 to 94 % with the material type therefore particle size. Calculated saturated hydraulic conductivity values (Hazen equation) also varied across and within the tailings mass from $10^{-3}$ to $10^{-6}$ cm/s.

The positions of the contaminant fronts were considered in light of the information derived from these limited geotechnical analyses. The depths to which the various fronts have penetrated did not correlate directly to the saturated conductivity values, although generally there was deeper penetration in more permeable material (eg. at E10). In a layered tailings mass such as in Area #1, the subsurface drainage patterns will include both lateral and vertical flow. The geotechnical analyses could only provide approximate information about the vertical flow characteristics of each test pits area; moisture content, grain size distributions and calculated saturated hydraulic conductivity. The lateral sampling distances, and vertical sampling intervals were relatively large to determine flow patterns and controls on acid migration.

Detailed sampling in an area of desiccation and surface cracking around station E140 showed evidence of increased oxidation at depth due to the transport of oxygen and water to the exposed surfaces with lower pH and higher acidity, conductivity, sulphate and iron values along the crack. These cracks may have formed preferential flowpaths for acidic drainage and also allowed lateral transport of acidic drainage through a more conductive sand layer, underlying a less permeable silt layer, thereby contributing to the layered pH and contaminant profiles discussed herein.

## 3.4 Geochemical and Geotechnical

### 3.4.1 Degree of Oxidation

One conclusion of the report after eighteen months of exposure of the tailings mass was that the degree of oxidation (as indicated by paste pH) correlated with the calculated oxygen diffusion coefficient (De) for the surface layer, and in turn with the degree of saturation. Similar calculations of diffusion coefficients have been conducted for the 1988 survey data and are shown in Table 11. Two methods of calculating diffusion coefficients were used; the first is applicable to a wide range of porosity and saturation values but indicates a diffusion coefficient of zero for samples near saturation (Senes and Beak, 1986), the second is more applicable to near saturation samples (Silker and Kalkwarf, 1983).

The data were analyzed graphically. The control on the diffusion coefficient ($D_e$) is the degree of saturation ($S_r$). This is correlated with grain size in terms of the moisture retention properties (residual saturation or capillarity) of the porous material. This relationship is shown in Figure 14 with the degree of saturation plotted as a function of silt content. Graphs for the diffusion coefficients versus silt content, paste pH and neutralization potential are shown in Figures 15, 16, and 17. The equation used to calculate a diffusion coefficient plotted for each sample varied according to the degree of saturation; the Senes and Beak equation ($D_e$ 1) which was developed for oxygen diffusion was used for samples at less than 85 % saturation, and the Silker and Kalkwarf equation ($D_e$ 2) used for radon diffusion through soil covers, was used for the samples with greater than 85 % saturation.

As shown in these figures, the data did not indicate obvious trends in relating one parameter to another, but rather groupings of results were more apparent. This is reasonable in dealing with soil samples as most of the geotechnical characteristics are typically determined by a critical fraction of material, eg. clay content, beyond which there is no significant change in the behaviour of the material. It was shown in the log descriptions and geotechnical analyses (Golder) that silt samples were generally poorly drained

## TABLE 11

## CALCULATED DIFFUSION COEFFICIENTS

SURFACE SAMPLES

| HOLE | n | $S_r$ | pH Surface | pH Interval | pH Depth | $D_{e_2}$* $cm^2/s$ | $D_{e_2}$** $cm^2/s$ | GRAIN SIZE % Silt | GRAIN SIZE % Sand |
|---|---|---|---|---|---|---|---|---|---|
| E10 | 0.54 | 0.52 | 2.5 | 3.5 | 3.5 | 0.0155 | 0.0137 | | 81 |
| E30 | 0.54 | 0.76 | 2.5 | 2.6 | 3.1 | 0.0029 | 0.0028 | 62 | |
| E60 | 0.51 | 0.70 | 2.7 | 3.0 | 3.3 | 0.0045 | 0.0044 | | 80 |
| E80 | 0.51 | 0.86 | 6.0 | 4.7 | 5.5 | 0.0003 | 0.0007 | 71 | |
| E100 | 0.50 | 0.88 | 6.2 | 4.0 | 4.0 | 0.0001 | 0.0006 | 68 | |
| E120 | 0.55 | 0.75 | 2.7 | 2.6 | 3.7 | 0.0036 | 0.0034 | 82 | |
| E140 | 0.50 | 0.92 | 3.0 | 2.8 | 5.6 | 0.0000 | 0.0003 | 82 | |
| E160 | 0.59 | 0.90 | 3.0 | 6.5 | 6.4 | 0.0001 | 0.0006 | 88 | |
| E170 | 0.51 | 0.62 | 2.6 | 2.9 | 2.7 | 0.0081 | 0.0077 | | 63 |

DEPTH SAMPLES

| HOLE | INTERVAL (cm) | n | $S_r$ | pH Interval | $D_{e_2}$* $cm^2/s$ | $D_{e_2}$** $cm^2/s$ | GRAIN SIZE % Silt | GRAIN SIZE % Sand |
|---|---|---|---|---|---|---|---|---|
| E10 | 34.7-43.3 | 0.50 | 0.60 | 4.5 | 0.0087 | 0.0084 | | 81 |
| E30 | 19.5-29.5 | 0.50 | 0.65 | 4.6 | 0.0063 | 0.0061 | | 72 |
| E80 | 38.6-45.4 | 0.49 | 0.92 | 6.3 | 0. | 0.0003 | 70 | |
| E100 | 39.7-48.3 | 0.63 | 0.70 | 6.4 | 0.0077 | 0.0066 | 55 | |
| E120 | 23.7-32.3 | 0.62 | 0.70 | 5.9 | 0.0074 | 0.0063 | 80 | |
| E140 | 14.4-25.6 | 0.67 | 0.80 | 6.7 | 0.0033 | 0.0033 | 84 | |
| | 30.7-39.3 | 0.50 | 0.43 | 6.1 | 0.0191 | 0.0183 | | 72 |
| E170 | 12.2-23.8 | 0.47 | 0.73 | 2.5 | 0.0027 | 0.0030 | | 68 |

* Senes and Beak (1986)
** Silker and Kalkwarf (1983)

## SATURATION AS A FUNCTION OF SILT CONTENT

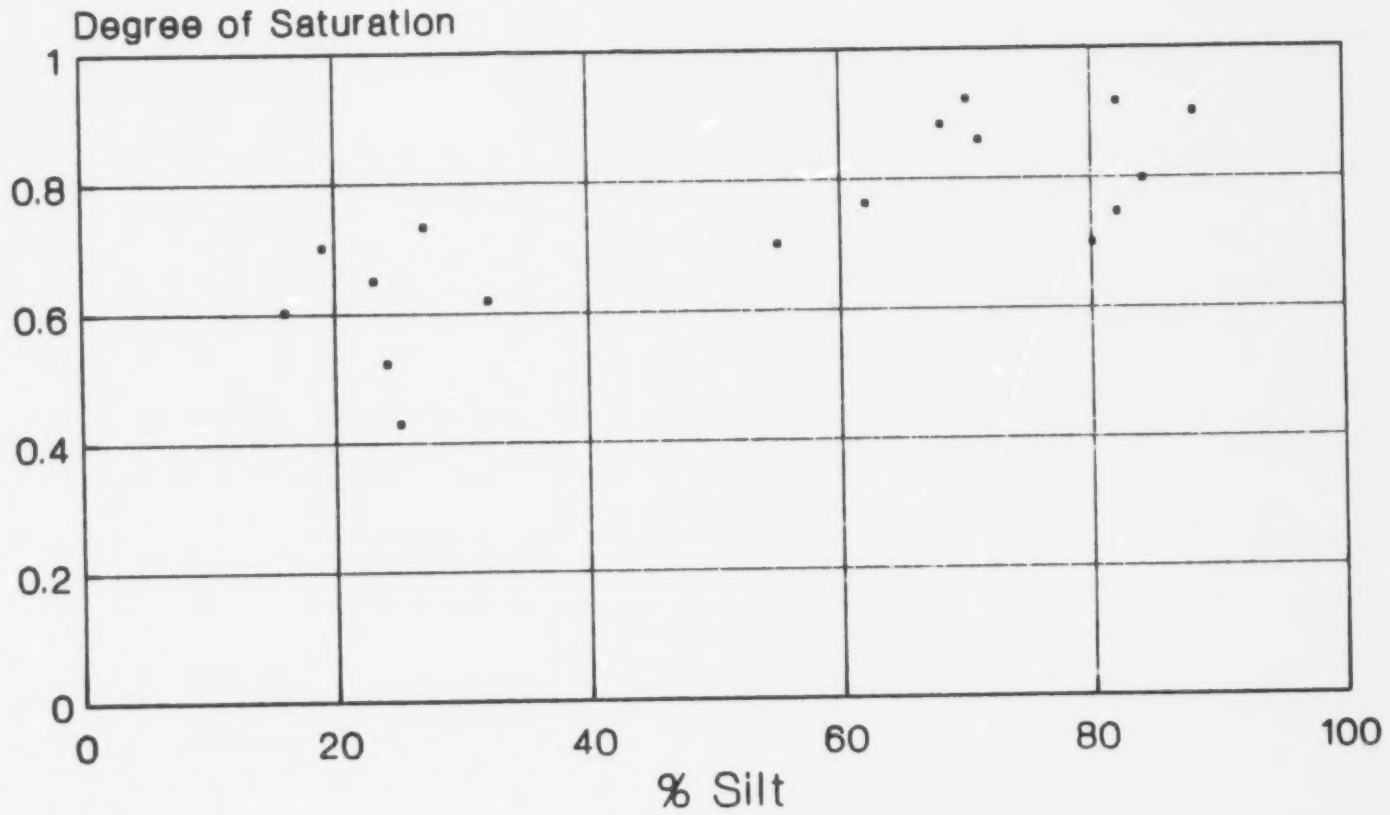



Figure 14

compared to sand samples. This is reasonable as residual moisture content in unsaturated conditions is related to grain size distribution (capillarity) of the porous material, tending to increased moisture content with finer grained materials. This pattern is shown in Figure 14, with two distinct groupings of samples apparent; a group of samples with 55 % to 88 % silt and greater than 70 % saturation in contrast to the sand samples with generally less than 70 % saturation.

As shown in Figure 15, the relation of the calculated diffusion coefficient and silt content of the sample was also grouped; silt samples generally had a lower diffusion coefficient than the sand samples E10 and E140 from 30.7 to 39.3 cm. These silts occurred at surface and at depth near the centre of the impoundment. A third group of points was evident in the sand samples with diffusion coefficients comparable to silt samples. This included surface samples from E60 and E170, and depth samples from E10, E30, and E170. The surface samples also had a high moisture content and might be located in low lying areas although it was difficult to distinguish this in Photographs 1 and 2. This distribution of points could be influenced by the heterogeneity of the tailings mass, as most of the characterization of the type of material in these samples differed slightly between the log descriptions and the fractional analyses. It must also be recognized that the sampling intervals were relatively large, and considerable layering and variation in material can exist within each interval.

Figures 16 and 17 show non-linear decreasing paste pH and neutralization potential as a function of diffusion coefficient for surface samples. The "surface" sample refers to the top 2 cm of the tailings mass, the "surface interval" or "surface unit" sample refers to the sample taken from the surface interval A as shown in the test pit logs and the "surface depth" refers to the pH value calculated over the depth of the "A" sample (geotechnical) as shown in the logs. The 1987 survey showed that at a diffusion coefficient of less than 0.0005 $cm^2/s$ or less, there was little pH depression or depletion of neutralization potential in surface samples. The results of the 1988 survey showed very similar results although the contrast was more marked in the 1988 results; at a diffusion coefficient of greater than 0.0007 $cm^2/s$ significant pH depression had occurred with essentially all of the surface and surface unit samples between pH 2.5 and 3, typical of oxidized tailings material. At

# DIFFUSION COEFFICIENT AS A FUNCTION OF SILT CONTENT

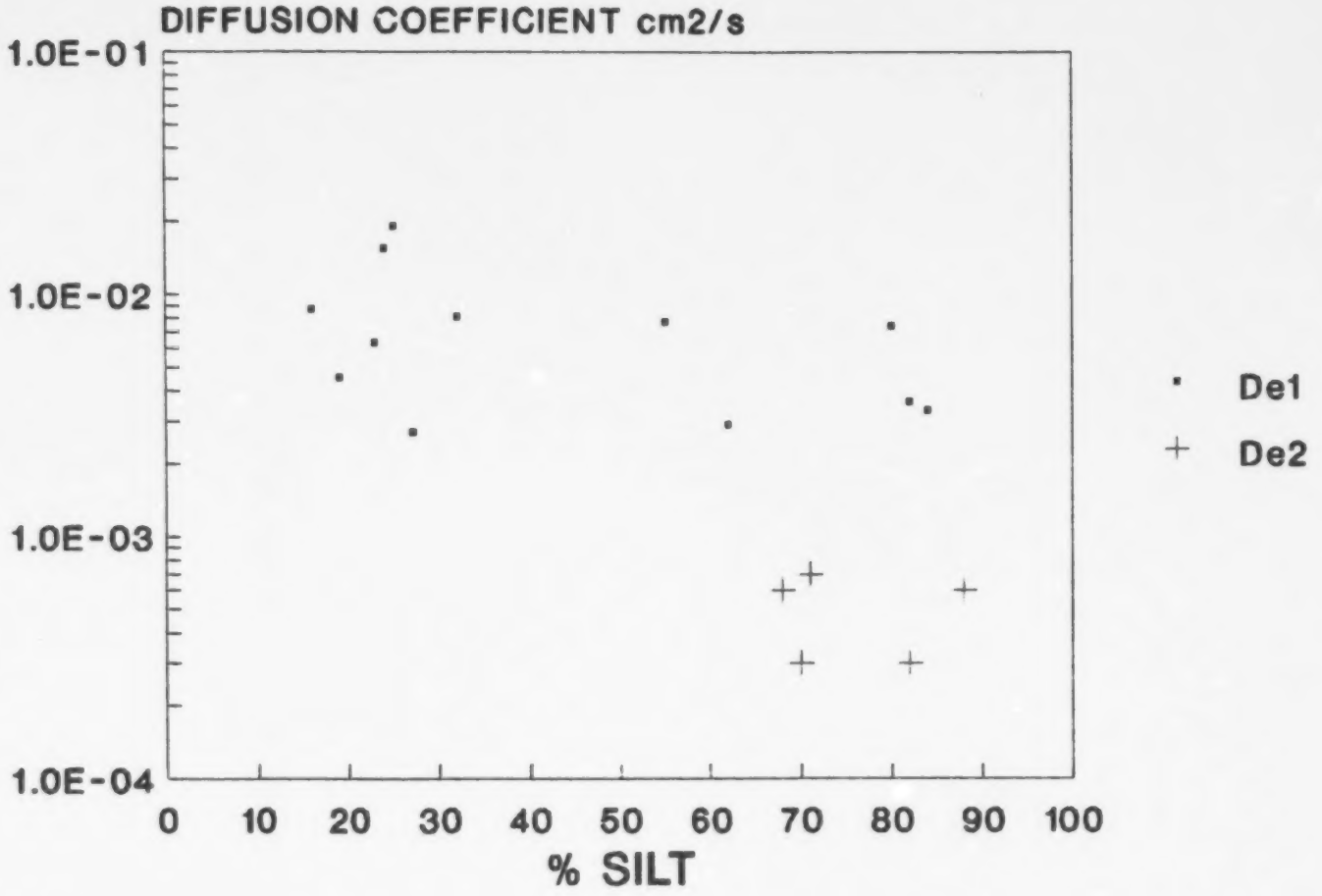



Figure 15

## DIFFUSION COEFFICIENT AND PASTE pH
## AREA #1 SURFACE/NEAR SURFACE SAMPLES

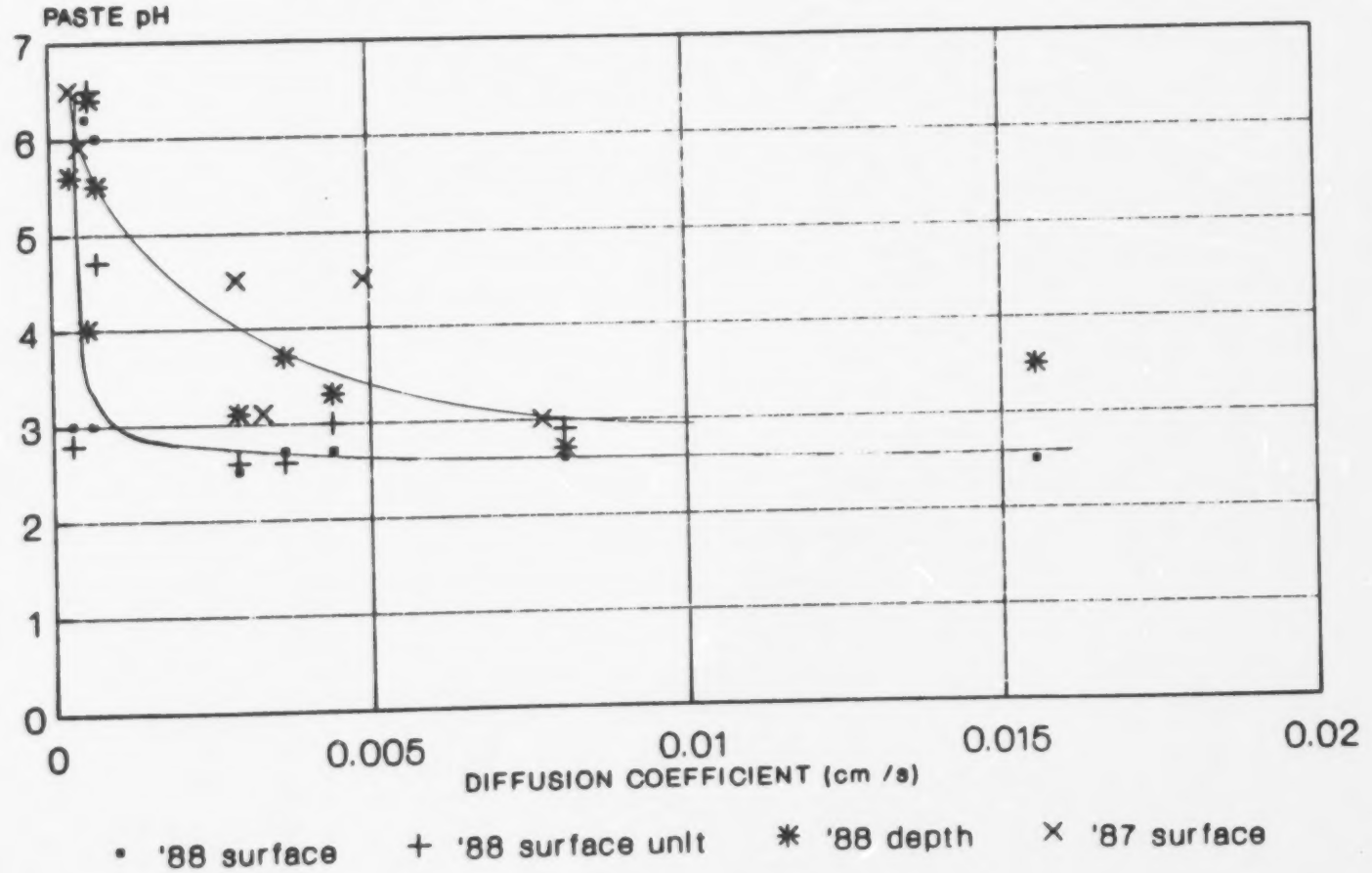



Figure 16

## DIFFUSION COEFFICIENT AND NEUTRALIZATION POTENTIAL

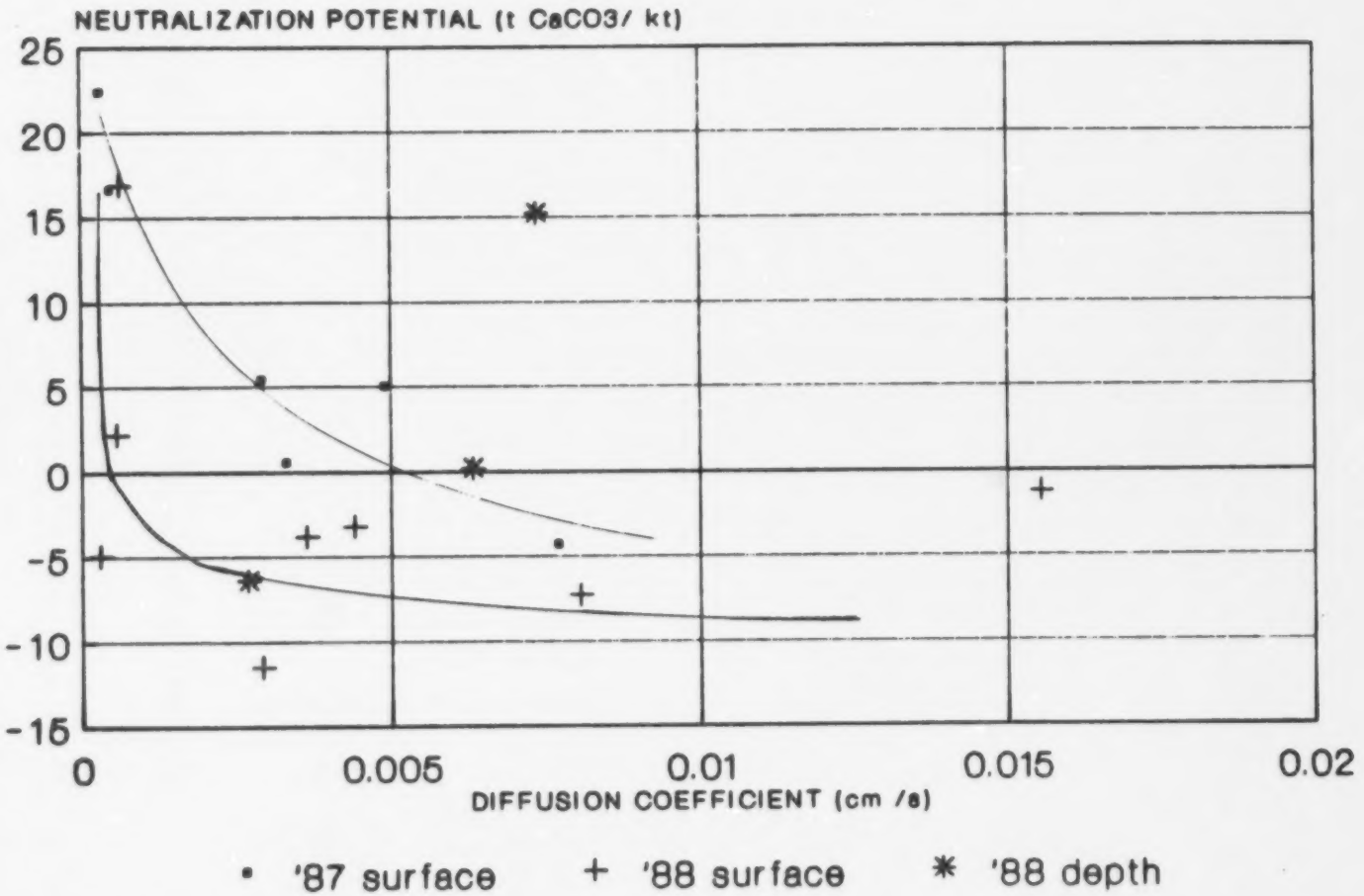



Figure 17

lower diffusion coefficient values, pH values ranged as high as 6.5, indicating relatively little oxidation had occurred. In the 1987 survey, only one sample with a diffusion coefficient of 0.007 cm2/sec exhibited a paste pH of 3. Thus the additional twelve months allowed sufficient oxygen to be transferred through the layers with a diffusion coefficient from 0.0007 to 0.007 cm2/sec to cause acid production and a depression in pH. The results of the "depth" samples generally corresponded to this pattern of depressed pH at higher diffusion values, however several samples appeared anomalous. This can be attributed to the layered nature of the tailings; layers ("unit" samples) were selected based in visual appearance whereas the geotechnical samples ("depth" samples) frequently spanned more than one layer and thus sometimes encompassed both low and high pH layers.

Paste pH values did not correspond with diffusion coefficients for samples at depth and were not presented in this figure. This is reasonable as the overlying strata would control the diffusion of oxygen to the layer samples and thus the layered heterogeneity of the tailings mass, and the variation in $D_e$ values with the material type would also affect the extent of the oxidation at depth in the tailings mass. In addition, the paste pH of a zone may be due to the migration of contaminants released by oxidation of surface zones rather than by direct oxidation of the deeper zone. The paste pH values at depth were graphed as a function of the diffusion coefficient of the overlying surface layer however no direct correlation was evident.

Significant depletion of neutralization potential (NP) was shown for most surface samples with a diffusion coefficient greater than 0.0007 $cm^2/s$ in the 1988 survey. Generally the tailings samples tested in 1988 had lower NP values than the 1987 samples and curves of NP depletion versus diffusion coefficient were similar to those for paste pH versus diffusion coefficient. Surface samples E100 and E160 however still showed positive neutralization potentials, and pH values between 3 and 6.5 within the near surface layers. The calculated diffusion coefficient values of these samples was less than 0.0007 $cm^2/s$. The surface sample at E140 appeared slightly anomalous with a low diffusion coefficient however it was depleted of neutralization potential.

The effective diffusivity of a soil layer determines the rate of oxygen transport through the layer, and thus the oxidation rate of the underlying material. Collin (1987) and Rasmuson and Collin (1988) have developed a

mathematical model for the transport of oxygen and water through layered soil covers, and described a method for calculating oxygen flux through a layered column of soil. This requires more detailed knowledge of oxygen uptake by sulphide minerals and diffusion coefficients for each layer than is available in the 1988 data, however their model could be a useful tool to evaluate methods to predict and control the generation of acid drainage.

### 3.4.2 Contaminant Transport

The transport of contaminants in acidic drainage is determined to a large extent by the hydraulic conductivity of the tailings mass, and the effects of diffusion and dispersion. The grain size distribution data were used to calculate saturated hydraulic conductivity values for each of the geotechnical samples which are provided in Tables 9 and 10. Conductivity values based on grain size data are primarily useful as order of magnitude estimations for sandy material, and assume saturated conditions. When this calculation is applied to soils with any significant percentage of silt, the hydraulic conductivity value can be overestimated by up to 2 orders of magnitude. Saturated hydraulic conductivity values for sandy tailings are generally within the range of 1 to 5 x $10^{-5}$ cm/s for low confining pressures and tend to decrease with increasing confining pressure or silt content (Knight and Piesold, 1989). Most the Westmin tailings were largely unsaturated, and in unsaturated soils, hydraulic conductivity increases with increasing moisture content.

The saturated hydraulic conductivity values calculated for the geotechnical samples did not appear directly related to the position of the contaminant fronts as shown in Figures 12b and 12c, (assuming vertical flow) although the depth of the front did correspond to conductivity for some samples. The lowest value of hydraulic conductivity was noted for sample E80, at 9 x $10^{-6}$ cm/s for both surface and depth. The average mean depth of all contaminant fronts at this site was the most shallow of all test pits, with all fronts at less than 26 cm depth except zinc, at 58 cm depth. These samples averaged 90 % saturation. In contrast, one of the highest conductivity values was calculated at E160 (1 x $10^{-4}$ cm/s) at surface in a

silt layer approximately 20 cm thick, and yet the contaminant fronts appeared between 28 and 35 cm depth. This sample was also at 90 % saturation. It is likely that there is a significant horizontal component to the drainage in the tailings mass, a design feature of subaerial impoundments.

The contaminant fronts have penetrated deepest in holes E10, E30, and E120. At E10, the test pit was predominantly sand material with relatively high hydraulic conductivity values ($10^{-4}$ cm/s at surface and $10^{-3}$ cm/s at depth). Three of the fronts have progressed to at least 80 cm depth. At E120, most of the fronts have progressed to the depth of the hole (64 cm), despite the extensive silt layers with low conductivity ($10^{-6}$ cm/s) indicated in the fence diagram. As mentioned previously, cracking near this hole appeared to play a major role in promoting contaminant transport. The layering in this hole was evident in the variable contaminant concentrations over depth from the shake flask data. Hole E30 was similar to E120 in the pattern of alternating sand and silt layers. The samples from E30 showed slightly higher hydraulic conductivity at both surface (sand/silt layer) and depth (sand layer) than E120 but shallower contaminant fronts.

Calculations were made of the vertical infiltration rate of the contaminant fronts using the depth of the front after 30 months of exposure. Sulphate and zinc are generally considered conservative reactants, and the zinc and acidity fronts have been shown to be most mobile. Therefore the flow rate calculated from the position of the zinc front has been used in the following table as representative of the unsaturated infiltration rate (or advective velocity) at each hole. The average saturated conductivity was calculated by assigning hydraulic conductivity values to the layers identified in the test pit logs, using the results of the geotechnical analyses. This is a very simplified analysis, as infiltration rates in unsaturated media are affected by a number of parameters, notably, suction pressures at the advancing front which can significantly affect the hydraulic gradient. This gradient can vary over depth in the tailings mass, and height above the underlying drainage layer, and tend to decrease with depth of penetration of the wetting front. Measurement of such hydrogeological parameters in the unsaturated tailings mass would require more sophisticated instrumentation and was beyond the scope of this study. Hydraulic gradients were not measured in the field and thus unsaturated conductivity cannot be calculated, however the

contrast between the unsaturated infiltration rate (I) and saturated parameter (K) was significant as shown:

COMPARISON OF SATURATED HYDRAULIC CONDUCTIVITY AND UNSATURATED INFILTRATION RATE

| HOLE | Unsaturated I (cm/s) | Saturated K (cm/s) |
|---|---|---|
| E10 | $> 1.2 \times 10^{-6}$ | $1.0 \times 10^{-3}$ |
| E30 | $> 7.7 \times 10^{-7}$ | $7.9 \times 10^{-4}$ |
| E60 | $> 6.4 \times 10^{-7}$ | $5.8 \times 10^{-4}$ |
| E80 | $7.2 \times 10^{-7}$ | $6.1 \times 10^{-4}$ |
| E100 | $7.5 \times 10^{-7}$ | $6.9 \times 10^{-4}$ |
| E120 | $> 8.2 \times 10^{-7}$ | $3.1 \times 10^{-4}$ |
| E140 | $> 6.8 \times 10^{-7}$ | $2.9 \times 10^{-4}$ |
| E160 | $4.5 \times 10^{-7}$ | $6.6 \times 10^{-4}$ |
| E170 | $3.6 \times 10^{-7}$ | $7.5 \times 10^{-4}$ |

NOTE: unsaturated infiltration rates calculated for test pits in which the depth of the zinc front extended to at least the depth of the test pit are denoted as ">".

Using the highest calculated vertical infiltration rate of $1.2 \times 10^{-6}$ cm/sec and assuming a depth of 3 m, breakthrough of the zinc front might occur in about 8 years. This estimate must be viewed with caution since the tailings layers at depth may have much lower hydraulic conductivity, infiltration rates could only be determined for four holes, and flow may be horizontal in some parts of the impoundment. Further study is required to determine if fronts have continued to move within the tailings mass.

These calculations indicated a significant difference between the saturated and unsaturated hydraulic conductivity, and saturated values cannot be used to predict the position of the contaminant fronts in the Westmin tailings. Assuming that zinc is essentially a non-reactive constituent, and thus the movement of the fronts represented the advective groundwater flow velocity, retardation mechanisms (such as chemical reactions) have affected the movement of most of the other monitored constituents of the acidic drainage.

The analysis above assumed simple vertical movement of the contaminants, however, the fence diagrams Figure 12b and 12c suggested a possible horizontal component of flow, particularly along more conductive sand layers. This would be reasonable given the layered nature of the tailings and the lack of correlation between geotechnical parameters (vertical hydraulic conductivity), and the position of the contaminant fronts. The shallow penetration of the fronts at E80 and increasing depth towards E10 suggests there could be a localized perched water table affecting flow in this area. Geotechnical samples were not however collected from the sand from 17 to 26 cm in E80 to determine if saturated conditions were present. Wet silty material was noted overlying this layer in the logs. In 1987, surface water was found flowing in a channel through this area. Possibly, flow may be largely horizontal through the sand layer from E80 to E10 and thence to the backdrain. If this horizontal flow does occur and if the horizontal conductivity is much greater than the vertical as suggested by the designers of the facility, contaminants may reach the backdrain through the sand layer sooner than the 8 years calculated above for vertical breakthrough. In addition, the cracking noted around stations E120 and E160 provided flow paths for the acidic drainage from near surface, and access to underlying sand layers for horizonal flow. Site E170, which was less affected by cracking and was at a high spot near the spray bar beach might represent more "typical" vertical flow.

## OXIDATION RATE

An approximate rate of oxidation in the tailings impoundment was calculated using the sulphate concentrations from the shake flask data, and tailings density values from the geotechnical data. The assumptions which were made included; that the bulk density of layers not sampled for geotechnical analyses was assumed based on the log descriptions and densities available for similar layers, that gypsum formation/dissolution was not a factor at these sulphate concentrations, that the depth of the oxidation zone was defined by a paste pH of 4.5 or less and that the oxidizing tailings material is 34 % sulphur (Ferguson, 1986). As discussed previously, in most test pits the surface layers exhibited a pH of 4.5 or less, however, in E120 and E160, areas of cracking, deeper isolated sand layers which underlay silts

also exhibited low pH. These deeper sand layers were assumed to be undergoing oxidation. Determination of the depth material actually undergoing oxidation, as distinguished from material into which contaminants were transported is difficult. It is recognized that the pH and acidity fronts do not necessarily represent the furthest point of advance of the oxidation front due to the neutralization potential of the tailings (Nicholson, 1989). However the limit of pH 4.5 or less generally corresponded to depleted neutralization potential and thus the point at which acid generation and contaminant loading rates became severe, and probably the zones in which the bulk of the sulphate was produced.

The oxidation rates were calculated based on sulphate production for a column of tailings and expressed:

i) per unit surface area for a column of tailings (mmoles $SO_4^{-2}/m^2$/month),

ii) per gram of material within the zone actually undergoing oxidation (mmoles $SO_4^{-2}$/g/month),

iii) per gram of sulphur within the zone undergoing oxidation (mmoles $SO_4^{-2}$/g S/month).

These calculations assumed that all of the sulphate that had been produced by oxidation in Area #1 was represented by the samples taken as for all pits, except for E120, the sulphate fronts were located within the test pits. The oxidation rates calculated for E120 therefore underestimate the actual rate. In the first calculation, the total amount of sulphate produced over 30 months was calculated from the shake flask data (background sulphate concentration of 140 mg/L was subtracted) and expressed as production per square meter of tailings surface per month. The next two calculations were based on the depth (or thickness) of the oxidation zone as defined by pH 4.5. Thus the previously calculated sulphate production (or oxidation rate) on a monthly basis was expressed in terms of the mass of tailings that have oxidized, and the mass of sulphur within this oxidation zone.

Sample Calculation of Oxidation Rates from Sulphate Production
for Test Pit E10, Shake Flask and Geotechnical Data

Where:

R = mass of sulphate produced per gram of sample in shake flask test
m = mass of sulphate produced per layer in column of unit surface area
M = mass of sulphate produced per column of unit surface area
  = sum of m
T = total $SO_4$ in mmoles produced over column per month
O = oxidation rate assuming oxidation and sulphate production occurs from layers of pH<4.5.
d = weighted average dry density over column of unit surface area

Calculations:

$R_A$ = 9.2 mg $SO_4^{-2}$/g solid

$m_A$= mass tailings x R
  = volume tailings x dry density x R
  = .23 $m^3$ x 1.65 $t/m^3$ x 9.2 mg/g
  = 3.49 kg
  = 3490 g

Calculate $m_B$ to $m_E$ similarly

$$T = \frac{M}{(96\ g/mol)(30\ months)}$$

$$= \frac{15{,}524\ g}{(96\ g/mol)(30\ months)}$$

= 5.39 mol/$m^2$ column surface area/month
= 5390 mmol/$m^2$ column surface area/month

$$O = \frac{T}{d\ g/m^3 \times \text{depth of oxidation zone}}$$

$$= \frac{5390\ mmol}{.48 \times 1.73 \times 10^6}$$

= $6.49 \times 10^{-3}$ mmol $SO_4^{-2}$/g solid/month

At approximately 34 % sulphur, O = $1.9 \times 10^{-2}$ mmol $SO_4^{-2}$/g S/month

CALCULATED OXIDATION RATE

| HOLE | $\frac{\text{mmoles } SO_4^{-2}}{m^2 \cdot \text{month}}$ | $\frac{\text{mmoles } SO_4^{-2}}{g \cdot \text{month}}$ | $\frac{\text{mmoles } SO_4^{-2}}{g\ S \cdot \text{month}}$ | Depth of Oxidation (cm) |
|---|---|---|---|---|
| E10 | $5.4 \times 10^{+3}$ | $6.5 \times 10^{-2}$ | $1.9 \times 10^{-2}$ | 49.0 |
| E30 | $1.5 \times 10^{+3}$ | $1.0 \times 10^{-2}$ | $3.0 \times 10^{-2}$ | 9.0 |
| E60 | $2.3 \times 10^{+3}$ | $5.6 \times 10^{-3}$ | $1.7 \times 10^{-2}$ | 23.0 |
| E80 | $2.1 \times 10^{+3}$ | $1.0 \times 10^{-2}$ | $3.0 \times 10^{-2}$ | 6.0 @pH 4.7 |
| E100 | $3.5 \times 10^{+3}$ | $1.6 \times 10^{-2}$ | $4.7 \times 10^{-2}$ | 12.0 |
| E120 | $3.4 \times 10^{+3}$ | $0.7 \times 10^{-2}$ | $1.9 \times 10^{-2}$ | 31.0 |
| E140 | $2.3 \times 10^{+3}$ | $9.1 \times 10^{-3}$ | $2.7 \times 10^{-2}$ | 4.0 |
| E160 | $2.2 \times 10^{+3}$ | $1.1 \times 10^{-2}$ | $3.3 \times 10^{-2}$ | 11.0 |
| E170 | $3.3 \times 10^{+3}$ | $7.6 \times 10^{-3}$ | $2.2 \times 10^{-2}$ | 23.0 |

These data were compared to data presented by Halbert et al. (1983) in which laboratory sulphide generation rates were calculated for lead-zinc mine tailings. The tailings consisted of 15.9 % sulphur, 20.0 % Fe, 1.84 % Zn, and 0.06 % copper. In laboratory tests using these tailings and media containing Thiobacillus ferrooxidans, sulphate generation rates were $1.1 \times 10^{-1}$ mole/kg tailings per month at $6^{o}C$, and $1.17 \times 10^{-1}$ mole/kg tailings per month at $21^{o}C$. The calculated laboratory oxidation rates were slightly higher than the calculated field values for the Westmin tailings. This would be expected as the lab tests were conducted in agitated flasks, providing more optimum oxidation conditions (particularly oxygen transfer) than in the tailings mass.

The calculated oxidation rates per gram of sulphur were quite consistent although there was a trend to lower rates of oxidation for samples with a higher diffusion coefficient (Figure 18). Sands exhibited a higher diffusion coefficient than silts and might be expected to have a lower oxidation rate per gram of sulphur since the particles are coarser with lower surface area of exposed sulphides. Station E100 was slightly anomalous giving a somewhat higher oxidation rate per gram of sulphur compared to other holes. Possibly horizontal movement of sulphate in this area contributed to the total amount of contaminant found. It is also possible the oxidation values (based on

# SO4 PRODUCTION PER MASS SULPHUR VS De
## EE LINE TEST PITS

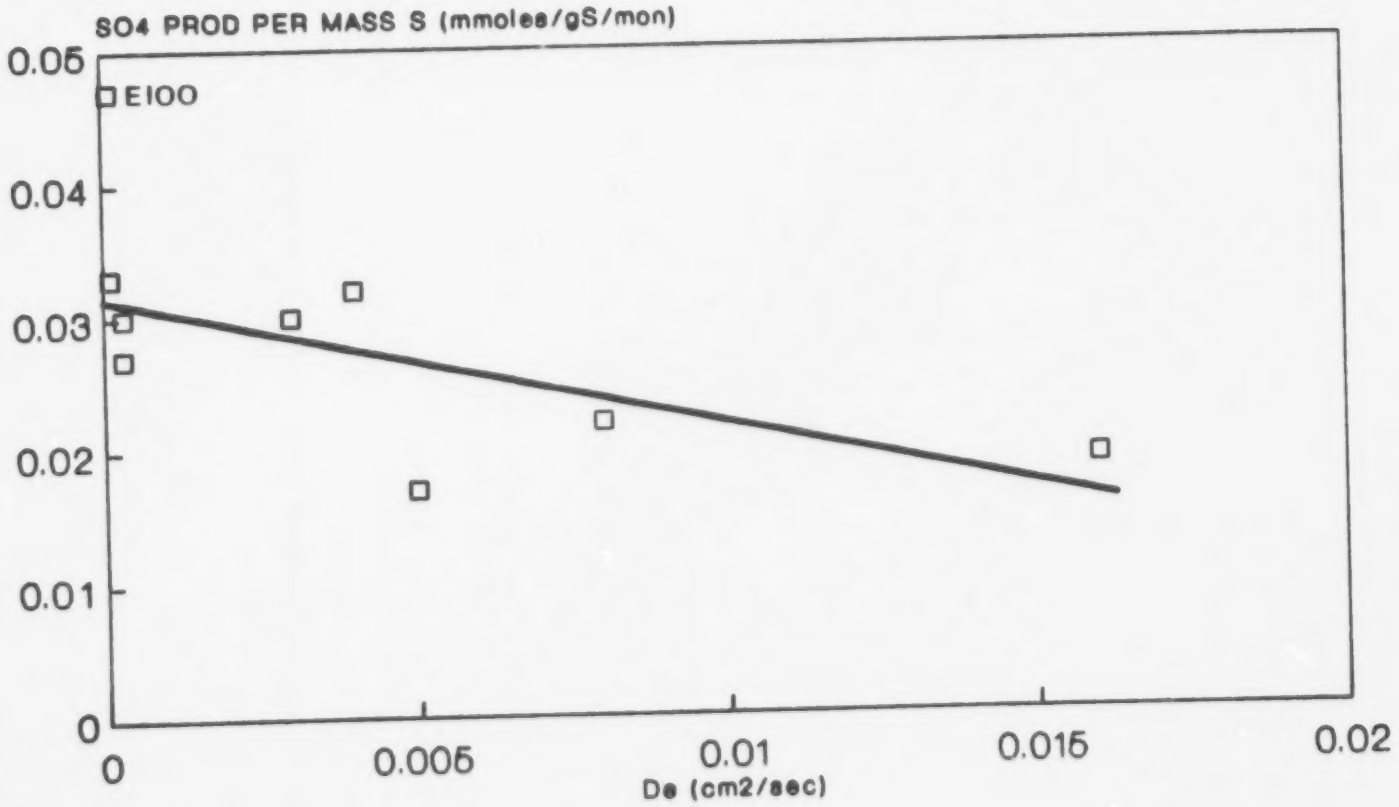



FIGURE 18

sulphate production are consistent if, during sample preparation, some further oxidation of the samples occurred, given that the samples were dried at 110°C in oxygen. This would probably only be significant for moderate to low oxidized tailings (Nicholson, 1989).

Holes with a higher diffusion coefficient exhibited a greater depth of low pH fronts, and by the conventions used in this report, greater depth of oxidation (Figure 19). It is important to note however that the extent of oxygen diffusion, infiltration and migration of oxidation products will vary with the particle size of the tailings (and thus the degree of saturation and the diffusion coefficient which are a function of particle size). In this way, the oxidation front can appear deeper in coarse material because:

i) there is deeper or more rapid penetration of oxygen because the diffusion coefficient is greater and

ii) less water is stored (that is, lower moisture content or residual saturation in unsaturated media) in coarse material so that the same water input at the surface moves further downward in the tailings mass.

Only E120, a hole exhibiting extensive cracking, differed slightly from the trend established by the other holes. According to the paste pH results, cracks around both E120 and E160 allowed movement of oxygen around a silt to oxidize a deeper sand that would otherwise not have been available for oxidation. This was evident when comparing the total depth of oxidation in E120 (31 cm) to E140 (4 cm) given a similar pattern in layering in the two holes. These cracks offered a vertical plane of exposed surface area for oxygen transfer and acid generation as shown by the limited testing of the crack pattern adjacent to E140, discussed previously. Oxidation products might move horizontally along less permeable boundaries. Sampling was not conducted to define these boundaries.

The oxidation rate per unit area indicated the total oxidation within the column of tailings is inversely related to the effective diffusion coefficients. Layers with a higher diffusion coefficient should have greater oxygen flux and should exhibit greater oxidation rate per unit area; as was found in this study (Figure 20). However, a doubling in the diffusion coefficient resulted in only a 1.3 times increase in the oxidation rate. It could not be determined if cracking significantly increased the rate of

oxidation in E120 as the limit of the sulphate front was not determined. The vertical limit of the front in E160 was determined, but not any horizontal movement of contaminants at a less permeable boundary, and therefore the calculated oxygen rate may have been underestimated. E100 had a somewhat elevated oxidation rate and E30 a lower rate given their respective diffusion coefficients.

## SUMMARY

Oxygen diffusion coefficients ($D_e$) were calculated for each of the geotechnical samples using two different equations; that of Senes and Beak, 1986, which was applicable to a wide range of porosity and saturation values but which indicated a diffusion coefficient of zero for samples near saturation, and that of Silker and Kalkwarf, 1983, which was more applicable to near saturation samples. Silt samples generally tended to have a higher degree of saturation and lower $D_e$ values than sands. Paste pH and neutralization potential decreased non-linearly as a function of the diffusion coefficient for surface samples, with little or no change at a $D_e$ value less than 0.0007 $cm^2/s$. These results were very similar to the 1987 survey. Paste pH values did not correspond similarly with diffusion coefficients for samples at depth. This could be explained as the overlying strata would control the diffusion of oxygen to the lower strata, and given the layered nature of the tailings, would affect the extent of oxidation at depth. A mathematical model has been developed to calculate oxygen transport through a layered cover, and the resulting oxidation rates. More detailed information about the diffusion coefficients of each layer, and oxygen concentration gradients within the tailings mass are required before these calculations could be applied to the Westmin tailings.

Saturated hydraulic conductivity values were calculated using the Hazen equation from the grain size analyses. This method provides an order of magnitude approximation but can significantly overestimate conductivity for fine grained silts. The calculated values did not correspond to the positions of each of the contaminant fronts, and thus saturated hydraulic conductivity values cannot be used to predict the flow of contaminants. Although there are areas in the tailings mass approaching saturation, the tailings are largely

## DEPTH OF OXIDATION VS De
### EE LINE TEST PITS

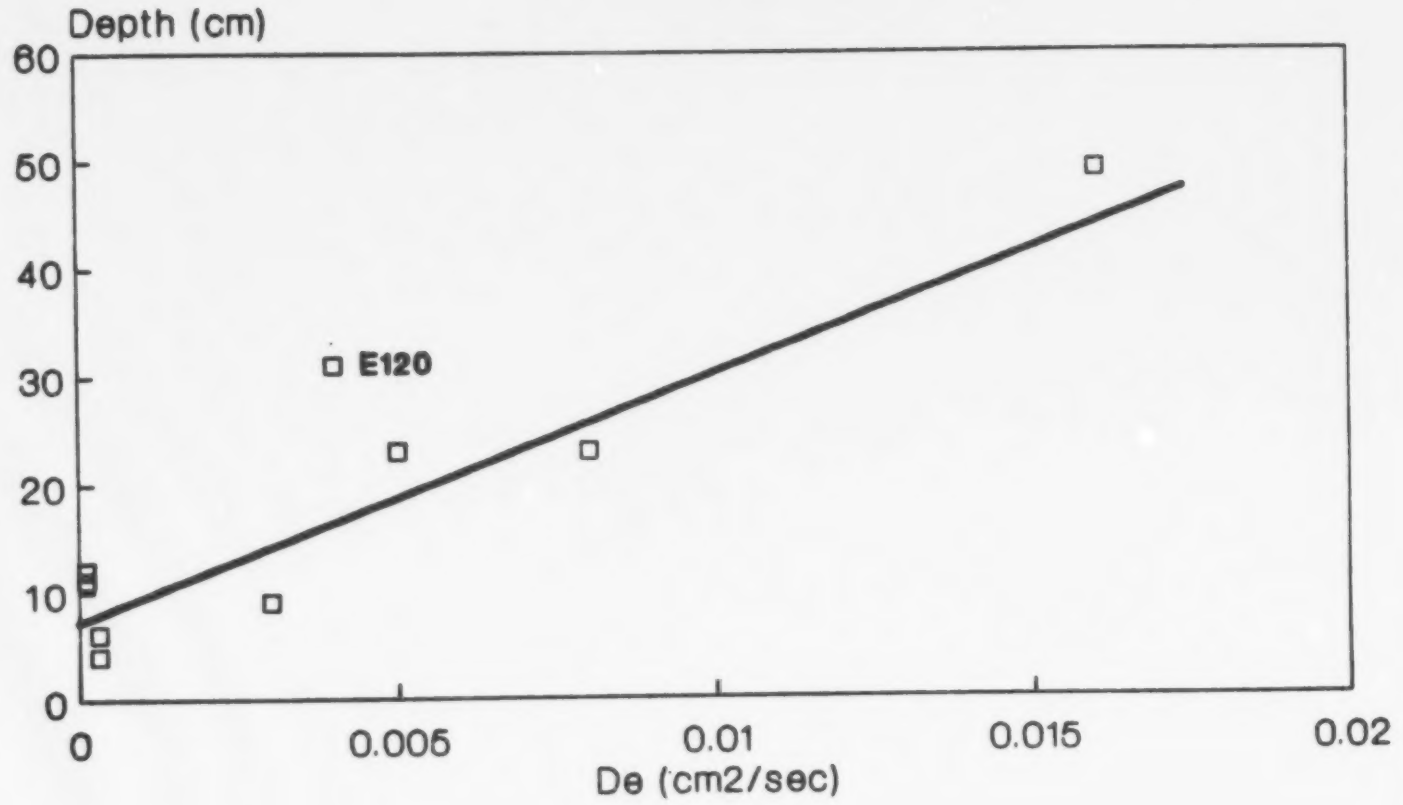



FIGURE 19

## SO4 PRODUCTION PER SURFACE AREA VERSUS DIFFUSION COEFFICIENT EE LINE TEST PITS

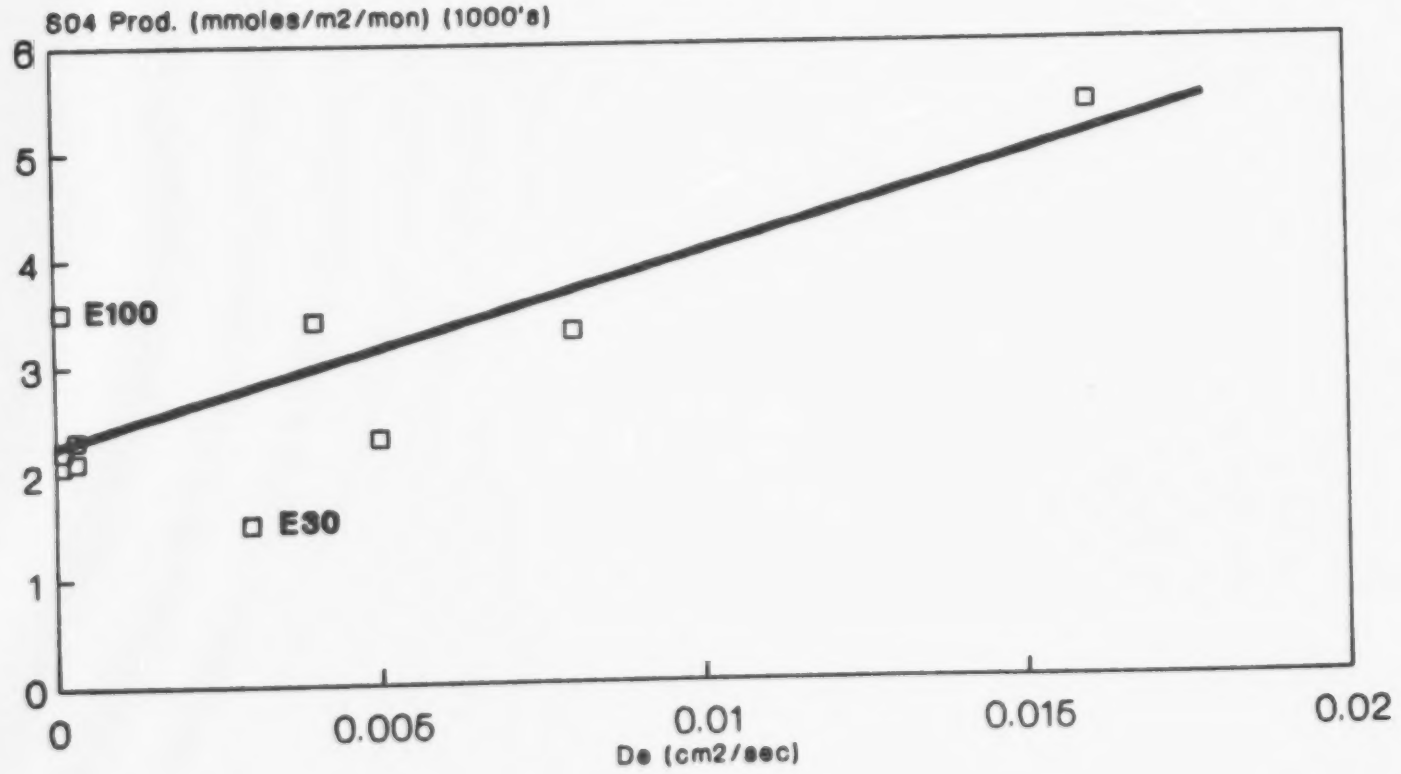



FIGURE 20

unsaturated and unsaturated hydraulic conductivity is less than the saturated.

The actual infiltration rate of each front, assuming vertical flow was also calculated and indicated that flow or conductivity was less than that suggested by calculated saturated hydraulic conductivity values. There was also some indication from the fence diagrams that there was a significant horizontal component of flow in the tailings mass, with transport of the contaminated water through more permeable sand layers rather than vertically through silt layers.

Using the highest calculated vertical infiltration rate of 1.2x10-6 cm/sec and assuming a depth of 3 m, breakthrough of the zinc front might occur in about 8 years. This estimate must be viewed with caution since the tailings layers at depth may have much lower hydraulic conductivity, infiltration rates could only be determined for four holes, and flow may be horizontal in some parts of the impoundment.

The shallow penetration of the fronts at E80 and increasing depth towards E10 suggests there could be a localized perched water table due to underlying silts, that may control the flow within the tailings mass in this area. Localized perched water tables might exist over silty layers throughout the impoundment, particularly after rainfall events. In addition, the cracking noted around stations E120 and E160 provided flow paths for the acidic drainage from near surface, and access to underlying sand layers for horizonal flow.

An approximate rate of oxidation in the tailings impoundment was calculated based on sulphate production and compared with published data (Halbert et. al). The calculated oxidation rates for the Westmin tailings were reasonable in comparison to the published lab data.

The calculated oxidation rates were roughly constant (from 2.8 to $7.9x10^{-2}$ or a factor of about 3) compared to the calculated diffusion coefficients for the surface layers (from 0.0007 to 0.018 or a factor of about 25). Holes with a higher diffusion coefficient and cracking exhibited a greater depth of oxidation. Higher diffusion coefficients also indicated greater oxidation. The effect of cracking on the oxidation rate could not be determined from this sampling program.

# 4 CONCLUSIONS

The following specific conclusions were drawn from the data and discussion of results presented in the preceding sections:

1. After 30 months exposure, sampling of the surface of Area #1 with testing for pH, ORP and TDS indicated that surface oxidation had progressed in Area #1, since the 1987 survey (after 18 months exposure). Only small isolated pockets were still above pH 2.5. These pockets might also be in areas of surface ponding as indicated in the site photographs and logs. A water cover can reduce the rate of acid generation, and localized areas of higher pH and lower ORP and TDS, seemed to correspond to ponded areas.

2. Surface solids samples showed large populations of Thiobacillus ferrooxidans in Area #1, indicating that bacterially catalyzed oxidation was occurring and well established on the surface of Area #1. Surface mapping indicated that areas with lower pH generally corresponded to more oxidizing redox potentials, and higher dissolved solids as would be expected if acid generating processes were established.

3. The cycloned sands from the backfill plant storage area did not indicate acid generation, even though it was thought that these samples had been deposited at least several months previously. The tailings sands have been shown (Ferguson, 1986) to exhibit a high potential to generate acid drainage. The lack of acid generation in these materials was therefore an unexpected finding.

4. Surface water quality sampling in the pool at the northeast corner of Area #1 (near the decant) indicated acid drainage with low pH and elevated contaminant levels in all samples. This pool appeared to be formed primarily from surface drainage from the Area #1 tailings. High concentrations of contaminants and Thiobacillus ferrooxidans noted in these waters were probably due to acidic runoff from oxidized surface areas of the impoundment.

5. The layered heterogeneous nature of the tailings, due both to the patterns of deposition, and the changing nature of the tailings (with changes in ore), was evident in the fence diagrams constructed from the test pit logs. Discrete layers have been formed as planned by the designers of the facility; these layers are extensive, but not continuous, across the impoundment. This may be due in part to the discontinuous operation of the cyclones and periodic discharge of tailings from the spigotting point on the north side of the facility.

6. Surface temperature measurements in Area #1 ranged from 11 to 15$^{o}$C and decreased rapidly with depth. Temperatures within the tailings mass appeared to be related more to the moisture content of the material, than to the effects of the exothermic oxidation reactions (as indicated by paste pH values). The effects of the different factors which control temperature change cannot be isolated from these data; generally wetter, silty soils recorded lower temperatures than drier sand, and also showed less evidence of oxidation. Ambient air temperature changes directly affected surface sample temperatures, although to a slightly lesser degree for wetter, siltier tailings than drier sand material. Temperature was not a good indication of acid generation at this site.

7. Paste pH profiles over the depth of each test pit demonstrated the effect of the layered nature of the tailings in controlling acid generation. The profiles varied over each hole; ranging from a low pH shallow surface layer with pH values increasing over depth, to a profile of alternating layers of acidic and neutral pH. Generally layers at less than pH 4 were orange/brown sands or orange/grey sand/silt mixes. Higher pH layers were typically moist grey/brown sands or wet grey silts.

8. Paste pH values decreased over the surface of Area #1 since the 1987 survey, and neutralization potentials were being depleted throughout the Area #1 at different rates. Depletion of neutralization potential was shown in samples with paste pH less than 3.5. At a pH value above 5,

neutralization potentials varied from 0 to 40 t $CaCO_3$/1000 t. Acid generation was much more established in 1988 compared to 1987.

9. Shake flask analyses of the test pit samples and fresh tailings were compared to determine the degree of change that had occurred in a variety of chemical parameters over time. There were significant changes in pH, acidity, conductivity and sulphate and dissolved metal production to differing degrees in various layers of the test pits. The largest changes were evident in samples within 30 cm of surface, although several surface samples showed little or no change. There were marked changes in some parameters (notably zinc) at depth, due to either surface cracking or the more permeable nature of that area (E10). Again the layered nature of the tailings, and the corresponding heterogeneity of the tailings mass resulted in variations in contaminants. Generally the conditions that promoted oxidation and acid generation through the tailings mass, can be listed, in decreasing order:

    1. cracking
    2. dry/sandy
    3. wet sandy
    4. silty
    5. wet silty

10. The positions of contaminant fronts were estimated based on empirical criteria of "elevated levels" of each parameter measured in shake flask tests. Zinc and acidity fronts seemed to be the first generated and/or the most mobile, occurring deeper than the other fronts in most test pits. Sulphate and conductivity fronts also appeared to be related occurring at the same depth in 50 % of the holes, and generally shallower than zinc and acidity fronts. The shallowest fronts were those of pH, copper and iron. This pattern is reasonable as copper and iron require low pH environments for mobility. Sulphate was probably the dominant anion and would therefore contribute most significantly to conductivity; this would explain the correlation between the two parameters. Zinc is the greatest contaminant of concern since it is migrating at the fastest rate.

11. Surface cracking was shown to allow oxidation at depth by providing a flow path for oxygen and water. Cracking also created preferential drainage paths for contaminants.

12. The layered heterogeneous nature of the tailings was again apparent in the test pits logs, and geotechnical testing of 18 surface and depth samples. The tailings ranged from sands to silts, with sand contents ranging from 1 to 82 %. Silts were generally more saturated as samples with 55 % to 88 % silt were greater than 70 % saturation in contrast to the sand samples with generally less than 70 % saturation. Generally, higher residual moisture contents would be expected for finer materials.

13. The diffusivity of the tailings was estimated from the calculated diffusion coefficient. The relation of the calculated diffusion coefficient and silt content of the sample was also grouped by material type; silt samples generally had a lower diffusion coefficient (< 0.01 $cm^2/s$) than the sand samples E10 and E140 at > 0.015 $cm^2/s$. A few sand samples had diffusion coefficients similar to silt samples, possibly due to the sample occurring in an area of surface ponding, or the heterogeneous nature of the tailings and the difficulties of obtaining representative samples.

14. The degree of oxidation as indicated by paste pH was related to the diffusion coefficient with significant pH depression evident at a diffusion coefficient of greater than 0.0007 $cm^2/s$, with most samples between pH 2.5 and 3, typical of oxidized tailings material. The diffusion coefficient is determined largely by the moisture content, and thus oxidation of the tailings was hindered by high moisture content. Saturation of the tailings however is contrary to the principle of subaerial deposition.

15. The diffusivity of the surface material controls the diffusion of oxygen to the underlying strata, and thus paste pH values did not correspond similarly with diffusion coefficients for samples at depth. Significant depletion of neutralization potential was shown for most surface samples

with a diffusion coefficient greater than 0.0007 $cm^2/s$ in the 1988 survey. Generally the tailings samples tested in 1988 had lower NP values than the 1987 samples. In general, both paste pH and NP were lower for similar diffusion coefficients in 1988 compared to 1987. The greater time for exposure allowed more cumulative oxidation.

16. The saturated hydraulic conductivity values calculated for the geotechnical samples did not appear directly related to the position of the contaminant fronts, although the depth of the front did correspond to conductivity for some samples. There was a significant difference between the saturated hydraulic conductivity and unsaturated infiltration rate of the tailings. Saturated values cannot be used to predict the position of the contaminant fronts.

17. The positions of the contaminant fronts and hydraulic conductivity calculations indicated that there could be a significant horizontal component to the groundwater flow in the tailings mass. Horizontal flow probably occurs through the more permeable sand layers. The presence of a perched water table near the centre of the impoundment was indicated by the position of the contaminant fronts, but there was insufficient geotechnical data to confirm its presence. In previous surveys, this was a low lying area through which surface runoff and ponding was noted. Discrepancies between the calculated and measured positions of the contaminant front may also be due to over-estimating hydraulic conductivity.

18. The rates of oxidation per surface area, per gram of tailings, and per gram of sulphur were estimated. The calculated rates agreed reasonably well with some published rates. Cracking controlled the depth of oxidation by exposing more surface area, and possibly the rate of oxidation though this could demonstrated by the available data. Increased diffusion coefficient of the surface layer and thus oxygen flux increased the depth and rate of oxidation. These findings are in agreement with the current understanding of sulphide oxidation in tailings.

The following conclusions are more general and were drawn from the overall evaluation of the results of this study:

1. After 30 months of exposure, acid generation was well established in the surface of the tailings, and to varying depths depending upon the geotechnical characteristics of the layers and the degree of cracking. As such, the subaerial method of tailings deposition did not appear to produce a tailings mass exhibiting a low potential for acid production. This prolonged exposure was not part of the original design but resulted from operational constraints which are common to mining and milling facilities.

   Rapid access to the impoundment for covering at closure of the facility is one objective of the subaerial disposal method and seems essential to prevent the onset of acid generation and surface cracking. Saturated and near saturated silt layers in the impoundment and particularly on surface did hinder oxidation. These layers were however prone to cracking due to desiccation, which allowed the transport of oxygen and water to depth in the mass for acid production. The presence of saturated layers is contrary to the design principles of subaerial tailings deposition, and thus a more conventional tailings disposal system with a continuous flooded impoundment might be more effective in inhibiting the generation of acid mine drainage.

2. Migration of contaminants from the surficial oxidized zone appeared to be much slower than predicted by saturated hydraulic conductivity. Since subaerial deposition generally produces an unsaturated tailings mass, the rate of movement of contaminants may also be much slower than in a conventional pond where much of the tailings at depth would be saturated. Unfortunately only four of the nine holes along the E-E line encountered the limits of the zinc front allowing back calculation of the unsaturated infiltration rate. Whether acid production is a concern depends upon the rate of migration of contaminants from the facility. Calculation of a mass flux of contaminants from the tailings could provide an indication of the potential drainage based on infiltration rates and contaminant concentrations. Further study of contaminant

transport is warranted to allow these calculations to be made with more confidence.

3. The results of this study cannot be used directly to predict the long-term behaviour of the Westmin tailings facility since the company plans to cover the tailings at closure. The results of this survey are of use, however, to assist in the design of other subaerial tailings facilities to limit acid generation, to describe the baseline conditions in the Westmin tailings without a cover, to provide input parameters (ie. oxidation rates) that may be of value in modelling performance of a cover design, and to indicate the length of time the tailings could be left exposed without encountering significant acid generation and contaminant migration.

4. The reasonably simple field and laboratory techniques used in this study were useful in developing insights into the factors that control acid production and contaminant transport in a very heterogeneous tailings mass. Even with these simple procedures, the field and laboratory time requirements were considerable. Programmes must be designed carefully to maximize collection of critical data. The paste pH and shake flask tests conducted at depth were particularly important analyses. Analyses of pore water (by squeezing techniques) and in-situ gas content, while requiring more sophisticated equipment, would be of great value to confirm the findings of this study. The importance of conducting studies over an extended time frame, with a good understanding of the baseline conditions (ie. during deposition, and after 18 and 30 months exposure as in this study) are important to develop an understanding of the temporal changes in an impoundment, particularly, during the early stages of acid generation.

# 5 RECOMMENDATIONS

Future studies should concentrate on determining the rate of contaminant migration in the facility. Since the 1988 survey was conducted, an additional lift of tailings was placed on Area #1. Test pits or auger holes through this fresh tailings area to the zone studied in the 1988 survey and beyond, are recommended to determine the horizontal and vertical migration of contaminants. Test pits or holes should be excavated as close to the E-E line as possible. Other recommendations for this further study follow:

- mapping of surface hydrology and drainage
- in-situ measurements of permeability
- calculation of retardation factors, testing in lab of samples which seem to show some retardation
- analysis of the changes in shake flask numbers from fresh to present.

Similar analyses should be done for all subsequent sampling programmes and the rate of change of each parameter (expressed as a percent change) evaluated. This could provide some indication of the rate at which acid generation has changed over the intervening time.

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